Particle Detector on a Plane

You may have observed airplane passengers accompanied by pets or even musical instruments on flights. But have you ever been seated next to a particle detector? [27]

Structures known as time crystals, which repeat in time the way conventional crystals repeat in space, have recently captured the interest and imagination of researchers across disciplines. [26]

Dreamt up by the physics Nobel laureate Frank Wilczek in 2012, the notion of "time crystals" is now moving from theory to experiment – and could also lead to applications such as a new kind of atomic clock. [25]

Yale physicists have uncovered hints of a time crystal—a form of matter that "ticks" when exposed to an electromagnetic pulse—in the last place they expected: a crystal you might find in a child's toy. [24]

The research shows that concentrated electrolytes in solution affect hydrogen bonding, ion interactions, and coordination geometries in currently unpredictable ways. [23]

*An exotic state of matter that is dazzling scientists with its electrical properties, can also exhibit unusual optical properties, as shown in a theoretical study by researchers at A*STAR. [22]*

The breakthrough was made in the lab of Andrea Alù, director of the ASRC's Photonics Initiative. Alù and his colleagues from The City College of New York, University of Texas at Austin and Tel Aviv University were inspired by the seminal work of three British researchers who won the 2016 Noble Prize in Physics for their work, which teased out that particular properties of matter (such as electrical conductivity) can be preserved in certain materials despite continuous changes in the matter's form or shape. [21]
Researchers at the University of Illinois at Urbana-Champaign have developed a new technology for switching heat flows 'on' or 'off'. [20]
Thermoelectric materials can use thermal differences to generate electricity. Now there is an inexpensive and environmentally friendly way of producing them with the simplest tools: a pencil, photocopy paper, and conductive paint. [19]
A team of researchers with the University of California and SRI International has developed a new type of cooling device that is both portable and efficient. [18]

Thermal conductivity is one of the most crucial physical properties of matter when it comes to understanding heat transport, hydrodynamic evolution and energy balance in systems ranging from astrophysical objects to fusion plasmas. [17]

Researchers from the Theory Department of the MPSD have realized the control of thermal and electrical currents in nanoscale devices by means of quantum local observations. [16]

Physicists have proposed a new type of Maxwell's demon—the hypothetical agent that extracts work from a system by decreasing the system's entropy—in which the demon can extract work just by making a measurement, by taking advantage of quantum fluctuations and quantum superposition. [15]

Pioneering research offers a fascinating view into the inner workings of the mind of 'Maxwell's Demon', a famous thought experiment in physics. [14]

For more than a century and a half of physics, the Second Law of Thermodynamics, which states that entropy always increases, has been as close to inviolable as any law we know. In this universe, chaos reigns supreme.
[13]

Physicists have shown that the three main types of engines (four-stroke, twostroke, and continuous) are thermodynamically equivalent in a certain quantum regime, but not at the classical level. [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.

Contents

Author: George Rajna

Preface

Physicists are continually looking for ways to unify the theory of relativity, which describes largescale 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.

How to get a particle detector on a plane

You may have observed airplane passengers accompanied by pets or even musical instruments on flights. But have you ever been seated next to a particle detector?

For more than a year, a small team at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) has been working to assemble, test, and transport detector pieces for an upgrade of the ALICE (A Large Ion Collider Experiment) detector array at CERN laboratory in Europe.

Detector panels ride as 'passengers'

The Berkeley Lab team's solution to ensuring that each of these carefully assembled, delicate pieces gets from Point A to Point B intact: treat them as travel companions.

ALICE, a nuclear physics experiment, is designed to collide high-energy lead ions with one another and with protons to explore an exotic state of superhot matter known as quark-gluon plasma that is thought to have existed in the early universe.

Berkeley Lab is one of five sites around the globe that is building detector panels (called "staves") for the upgrade project, which will improve the performance of the ALICE detector's inner tracking system—including its resolution to take snapshots of particle collisions, its durability, and data-collection speed.

Nuclear physics researchers at Berkeley Lab take turns in transporting four long detector staves at a time in a custom-built clear container equipped with a shoulder strap. When loaded, the meter-long container weighs about 25 pounds. The staves are stacked with sequences of silicon chips and related circuitry and power components.

Each stave the Berkeley Lab team is responsible for has eight sensor modules, and each module is equipped with 14 sensors, for a total of 112 sensors per stave.

Berkeley Lab researchers have been assembling components for an upgrade of the ALICE particle collider experiment's detector array at CERN laboratory. Learn about their work and how it could help to unravel the inner workings of an exotic state of matter known as the quark-gluon plasma in this short video. Credit: Marilyn Chung/Berkeley Lab

This seat is taken

"We ended up buying seats on commercial flights for them because there is no other reliable way to get them there," said Leo Greiner, a staff scientist in Berkeley Lab's Nuclear Science Division who leads the team working on the ALICE detector upgrade components.

The team had used mechanical models of the detector modules to see how they would hold up in an airplane's cargo hold, and they didn't fare well: The units were visibly damaged, with some parts breaking off.

"It was pretty clear the transportation couldn't happen in the way we originally envisioned," Greiner said. So he researched the best way to get the staves inside the cabin—a more protected environment. The rules for purchasing a seat for the staves are similar to those for expensive musical instruments that musicians want to hand-carry onto the plane, he said.

The clear, Berkeley Lab-built carrying case is designed for ease of airport security inspections, and airport X-ray scans are not a problem as the detector components are designed to withstand far more intense radiation.

Once aboard the plane, researchers request a seatbelt extension to safely buckle the carrying case into the adjoining seat. Their usual route is to fly to Newark or Washington, D.C., from the San Francisco Bay Area, and then to connect to an international flight to Geneva, Switzerland. The round trip usually involves two full days of travel and two days at CERN to check for any damage to the components.

Members of the Berkeley Lab team have completed about 14 of these trips over the past year, with the last trip scheduled for mid-October.

Nicole Apadula holds a custom-built carrying case designed for four detector staves. The case is hand-carried aboard commercial flights to ensure safe transport of the detector components to CERN laboratory in Europe. Credit: Marilyn Chung/Berkeley Lab

Science outreach made easy

The unusual carry-ons are quite a conversation starter, Greiner said.

"It's the most fantastic outreach I've ever done," he said. "Everyone has questions."

Nikki Apadula, a project scientist in the Nuclear Science Division and a member of the ALICE team who has participated in the detector excursions, said, "I spent an entire trip to Newark using the back of the seat to explain what particles do in the detector."

Apadula said that the tall travel containers can be cumbersome at times. "The fact that these things are a meter long—it's just awkward. It's almost as tall as me."

Other members of the Berkeley Lab's ALICE detector upgrade team, including research assistants Erica Zhang and Winston DeGraw, who both began working on the project as undergrads, have been the most frequent flyers on the detector trips.

Berkeley Lab’s Erica Zhang conducts measurements of a detector stave during assembly. Credit: Marilyn Chung/Berkeley Lab

Assembling the staves

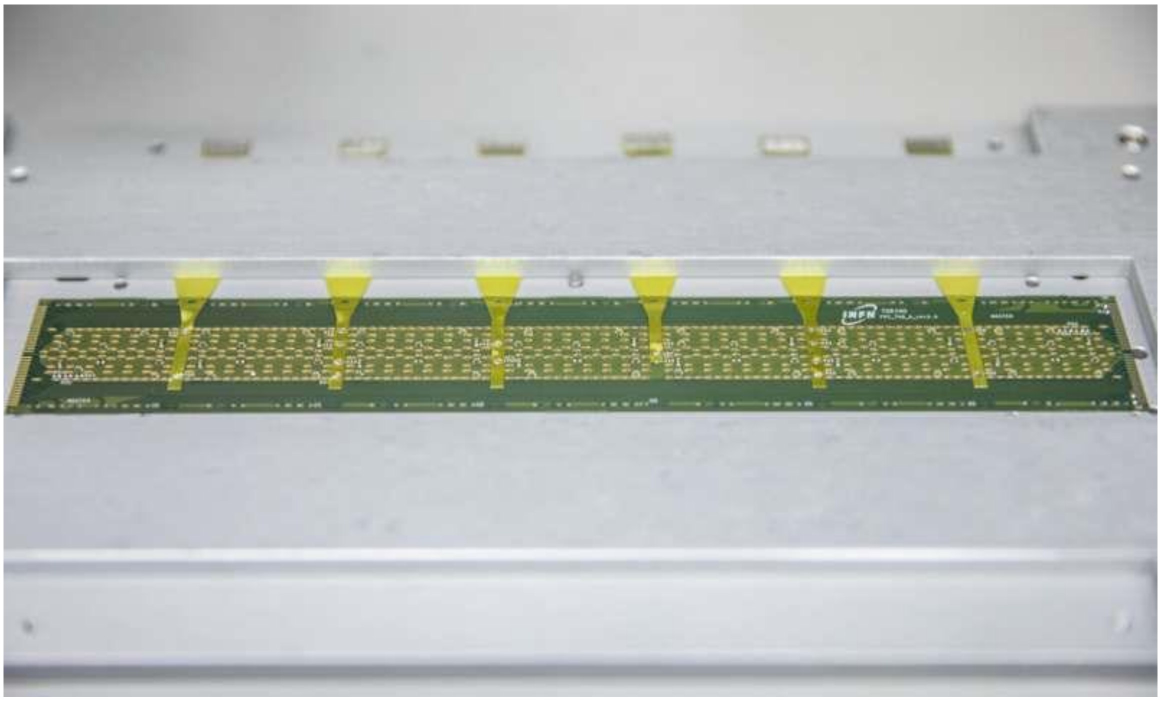
The Berkeley Lab team is contributing 60 detector staves for the middle layers of ALICE's upgraded outer-barrel detector—the largest contribution by a U.S. lab.

The completed detector will have seven concentric layers that will hold a total of 24,000 silicon sensors for detecting particle interactions. It is scheduled for installation in March 2020, and will be operational in early 2021.

Detector assembly at Berkeley Lab was conducted in a specially constructed plastic-walled clean room environment. Researchers carefully measured and glued eight detector modules to each stave, with accuracy typically measured in tens of microns, or tens of millionths of a meter.

The staves feature tubes that allow cool water to circulate along their length and prevent overheating, and all of the materials—down to the glue that affixes the detector modules—must be tested to ensure they can withstand the detector environment.

Each stave features a wedge-shaped carbon-fiber support along its length, and aluminum electrical components rather than copper to provide better tracking resolution to capture the particle interactions while withstanding the barrage of radiation produced in particle collisions. In the early stages of the project the Berkeley Lab team used powerful charged-particle beams at Berkeley Lab's 88-Inch Cyclotron to test the durability of the detector materials, Greiner noted.



These silicon chip components are prepared for placement on a detector stave. Credit: Marilyn Chung/Berkeley Lab

Next-gen detector design

The detectors in the upgrade are based on a monolithic pixel detector technology—an earlier generation of this type of detector was used for the STAR (Solenoidal Tracker at RHIC) detector at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). Berkeley Lab has particular expertise in this type of detector, Greiner noted, and contributed to early R&D.

The ALICE upgrade detectors are designed for a longer lifespan, can process signals about 10 times faster than earlier detectors, and have an individual pixel size of about 30 microns. The improved resolution will allow researchers to better differentiate particles produced in the initial lead nuclei collisions from those that branch out from the particle decays that follow these initial interactions.

"The technology has really matured," Greiner said. "They can take data more quickly, don't die as quickly, and dissipate less power."

Other assembly sites for the new detectors are in China, England, France, Italy, the Netherlands, and Korea. The ALICE collaboration numbers about 1,500 scientists from over 100 physics institutes in 30 nations. Berkeley Lab participation in ALICE is supported by the U.S. DOE Office of Science's Office of Nuclear Physics. [27]

Appreciating the classical elegance of time crystals

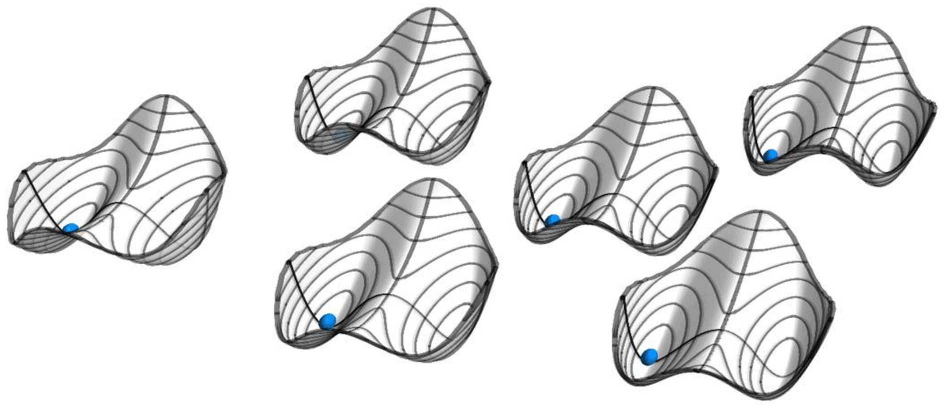
Structures known as time crystals, which repeat in time the way conventional crystals repeat in space, have recently captured the interest and imagination of researchers across disciplines. The concept has emerged from the context of quantum many-body systems, but ETH physicists have now developed a versatile framework that clarifies connections to classical works dating back nearly two centuries, thus providing a unifying platform to explore seemingly dissimilar phenomena.

In a crystal, atoms are highly ordered, occupying well-defined locations that form spatial patterns. Seven years ago, the 2004 Physics Nobel laureate Frank Wilczek pondered the possibility of a time analogue of crystalline spatial order—systems that display sustained periodic temporal modulations in their lowest-energy state. The concept of such structures with an oscillating ground state is highly intriguing. Alas, not long after the idea was published, it was proven that such time crystals are not possible without breaking fundamental laws of physics. However, subsequent theory work suggested that when quantum many-body systems are periodically driven, new persistent time correlations emerge that are evocative of Wilczek's time crystals. These driven systems were dubbed discrete time crystals, and in 2017, the first experimental realizations of such states were reported in ensembles of coupled particles (ions, electrons and nuclei) that display quantum-mechanical properties.

A not-so-brief history of time crystals

Before long, astute observers spotted distinct similarities between discrete time crystals in quantum systems and so-called parametric resonators, a concept in classical physics reaching back to work by Michael Faraday in 1831. The connection between these two bodies of work remained, however, opaque. Now, theorists have developed a new framework goes a long way toward lifting the ambiguities surrounding the similarities between periodically driven classical and quantum systems.

Writing in an article published today in the journal *Physical Review Letters*, Toni Heugel, a Ph.D. student in the Department of Physics at ETH Zurich, and Matthias Oscity, a student at the same institution, working with Dr. Ramasubramanian Chitra and Prof. Oded Zilberberg from the Institute for Theoretical Physics and with Dr. Alexander Eichler from the Laboratory for Solid State Physics, report theoretical and experimental work that establishes how discrete time crystals can be generated that, on the one hand, require no quantum mechanical effects and, on the other hand, display genuine many-body effects, which is a characteristic of discrete time crystals reported in quantum systems.



Quasi potentials of six parametric oscillators with weak all-to-all coupling. Stable solutions are located at the minima. The balls indicate the symmetric solution, where all oscillators are in phase. The Hamiltonian H govern the motion of the system has period T, while the solution itself has period 2T. This discrete time translation symmetry breaking makes the system a discrete time crystal. Credit: ETH Zurich/D-PHYS Toni Heugel

Many ways to subharmonic frequencies

There is one obvious similarity between classical parametric resonators and experimentally realized discrete time crystals in quantum many-body systems: Both display emergent dynamics at frequencies that are fractions of the drive frequency. In the context of discrete time crystals, the emergence of oscillations at such subharmonic frequencies breaks the temporal periodicity of the driven system, providing a 'time analogue' to crystalline spatial order, in which the symmetry of space is broken. In classical parametrically driven systems, subharmonic frequencies appear in more familiar ways: A child on a swing, for instance, modifies the centre of gravity at twice the frequency of the resulting oscillation, or the ponytail of a runner oscillates at half the frequency of the vertical head movement.

But do these dissimilar phenomena have anything to do with one another? Yes, say the ETH physicists. In particular, they pinpoint where many-body aspects appear in classical systems. To do so, they considered classical nonlinear oscillators with tunable coupling between them.

Unifying framework for periodically driven classical and quantum systems

It is well known that for certain driving frequencies and strengths, parametric oscillators become unstable and then undergo a so-called period-doubling bifurcation, beyond which they oscillate at half their driving frequency. Heugel, Oscity and their colleagues explore what happens as several such oscillators are coupled together. In calculations as well as in experiments using two strings with variable coupling between them, they find two distinct regimes. When the coupling is strong, the two-string system moves collectively, recreating in essence the movements of the child on a swing or the ponytail of a runner. However, in the case of weak coupling between the strings, the dynamics of each string are similar to those displayed by the uncoupled system. As a consequence, the coupled oscillators do not bifurcate collectively but bifurcate individually at slightly different parameters of the drive, leading to richer overall dynamics, which grow ever more complex as the systems get larger.

The ETH researchers argue that such weakly coupled modes are similar to the ones that emerge in quantum many-body systems, implying that their framework might explain the behaviors seen experimentally in these systems. Moreover, the new work prescribes general conditions for generating classical many-body time crystals. These could ultimately be used to both interpret and explore features of their quantum counterparts.

Taken together, these findings therefore provide a powerful unifying framework for periodically driven classical and quantum systems displaying dynamics at emergent subharmonic frequencies—systems that have been so far described in very different contexts, but might be not that dissimilar after all. [26]

In Search of Time Crystals

Dreamt up by the physics Nobel laureate Frank Wilczek in 2012, the notion of "time crystals" is now moving from theory to experiment – and could also lead to applications such as a new kind of atomic clock. **Philip Ball** explains

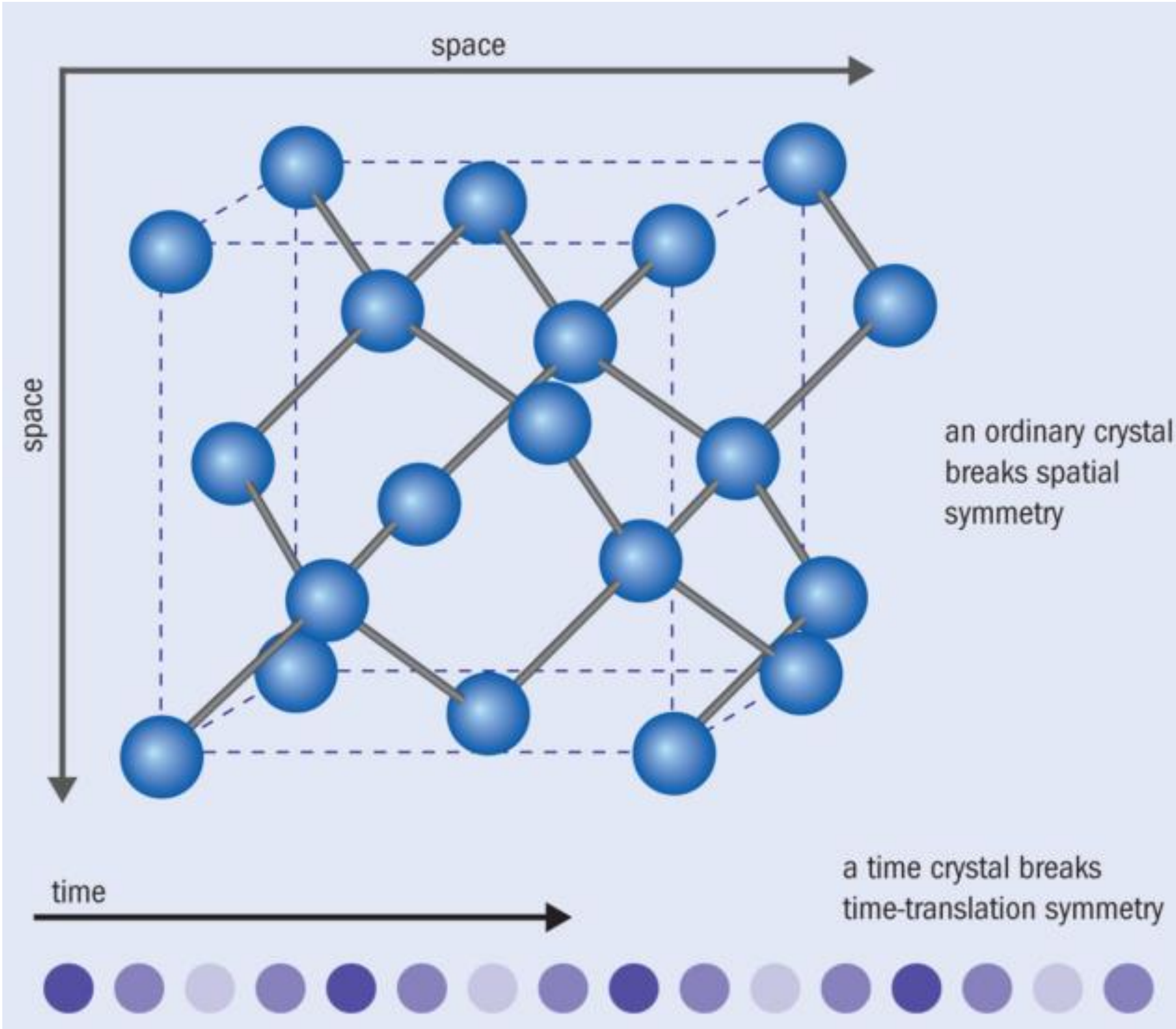
There's no point in denying that the appeal of an idea in science can depend on finding a catchy name for it. Just think of the Big Bang, black holes or dark matter. None of those, however, comes close to the *Doctor Who*-style resonance of the phrase "time crystals". But this concept, first proposed in 2012 by the Nobel-prize-winning physicist Frank Wilczek (*Phys. Rev. Lett.* **109** 160401), is more than a case of canny packaging. It toys with some deep themes in physics – the symmetry of time, quantum mechanics and the role of disorder – to come up with a counterintuitive new proposal for how matter can behave.

Ordinary crystals consist of atoms or molecules arranged regularly in space. But rather than having a periodicity in space, time crystals exhibit a periodicity in time. They display a dynamical, ever-changing mode of behaviour that repeats regularly. Although Wilczek's original concept of time crystals as materials that show spontaneous temporal periodicity has been invalidated, it's possible to produce a variant of what he had in mind by driving a system out of equilibrium. Last year time crystals of this other kind were demonstrated for the first time in the lab. And very recently two more varieties have been spotted, raising the possibility that time-crystal behaviour might be a rather common property of materials.

That's all very well, but are time crystals actually of any use? Some researchers think they could be used to make highly sensitive magnetic-field detectors or possibly even components of quantum computers. Their real value, however, could be to furnish a broader picture of how condensed states of matter can behave. For theorists exploring that question, says Norman Yao of the University of California at Berkeley, "all of a sudden we have a new playground".

Time for a break

To understand time crystals, let's remind ourselves about ordinary crystals. Diamond, say, breaks spatial symmetry because not every location is equivalent. Some locations have carbons atoms; others don't. If you shift, or "translate", the diamond lattice by some arbitrary amount, it won't superimpose on the original lattice; the crystal structure has broken the translational symmetry of uniform space. But if you shift the lattice by some integer multiple of the spacing between atoms, it does superimpose, which means that the broken translational symmetry is periodic.



1 A break in time

But what if a material could break “time-translation” symmetry – the symmetry that makes the system unchanged if you shift it forward by an arbitrary amount of time? In his original 2012 proposal, Wilczek considered a ring of quantum particles – the simplest 1D system without edges. He asked if there might be circumstances in which the lowest-energy state of this ring breaks time-translational symmetry such that it changes in time, but returns to the original state at periodic intervals (figure 1).

If a system could indeed break time symmetry, Wilczek reasoned, that periodic change might not necessarily entail the motion of the atoms themselves. Instead, it could perhaps be a periodic cycling of some other property, such as the orientation of their spins. Just as moving through space in an ordinary crystal seems to take you away from and then back to where you started – you come to another atom identical to the one you began at – so moving through time at some location in a time crystal will trigger a periodic departure from and return to your initial state.

Such spontaneous, continual change sounds "perilously close to fitting the definition of a perpetual motion machine", Wilczek admitted in his 2012 paper. But it needn't actually be that. After all, we already know of one type of quantum-mechanical ground state that supports a kind of motion indefinitely: a current circulating forever around a ring of superconducting material. But that's uniform motion. In a time crystal, the motion would oscillate – like, say, a Mexican wave of flipped spins circulating around Wilczek's ring of spins forever.

Question time

So far so good for time crystals, but in 2015 physicists Haruki Watanabe from the University of California, Berkeley, and Masaki Oshikawa from the University of Tokyo argued that the idea won't stack up. They showed that no physical system in its lowest-energy state can form a time crystal of the kind envisaged by Wilczek (*Phys. Rev. Lett.* **114** 251603). A similar objection had been previously stated more briefly by Patrick Bruno of the European Synchrotron Radiation Facility in Grenoble, France (*Phys. Rev. Lett.* **110** 118901).

The argument against time crystals is that there is no way to prevent such an oscillating system from dissipating energy, meaning that the oscillating state must gradually decay – it's not in equilibrium. Systems in thermal equilibrium cannot therefore have any interesting time dependencies – there will be nothing interesting that changes with time. So were time crystals just the futile fantasy of a Nobel-prize-winning theorist?

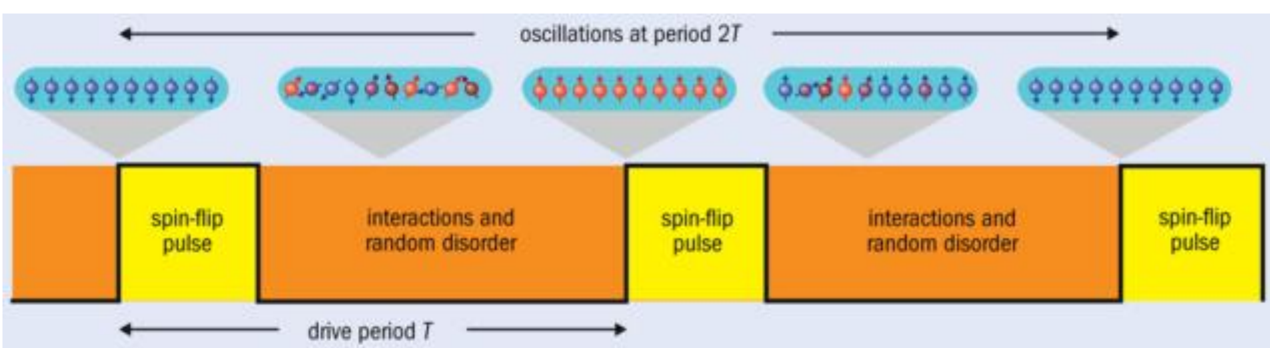
Not quite. Watanabe and Oshikawa admitted that there is a loophole in their argument against the existence of time crystals. Periodic "time-crystal" behaviour could exist, they said, in a system that is pushed out of equilibrium by some driving force. In effect, says David Huse of Princeton University, Watanabe and Oshikawa showed that to break time symmetry (and so get time-crystal behaviour) you'd also have to break some other symmetry too, as with a periodic driving force.

The fact that you could get time-periodic behaviour out of equilibrium might not seem that surprising. After all, oscillatory non-equilibrium states are well known already, as Watanabe and Oshikawa pointed out. Such states occur, for example, in the population cycles of ecosystems and in oscillating chemical reactions such as the well-known "clock reaction", which can keep switching states (and colours) indefinitely if continuously supplied with fresh reagents.

Given that such states exist, they shouldn't be awarded this fancy new label of time crystals "without a further justification", the two physicists warned. And in fact, quantum systems subject to some periodic driving force had been thought about long before Wilczek came to the idea of time crystals. They belong to a broader class known as "Floquet systems", named after the 19th-century French mathematician Gaston Floquet who worked out the maths needed to analyse them.

A discrete business

In one of those delightful "something in the air" convergences that science occasionally produces, the states that Floquet systems can adopt were being clarified at just the same time as, but independently of, the notion that such non-equilibrium time crystals can exist. In 2016 a team at Princeton and at the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany, showed that Floquet systems containing disorder can, paradoxically, give rise to phases that are periodically ordered in time (*Phys. Rev. Lett.* **116** 250401).



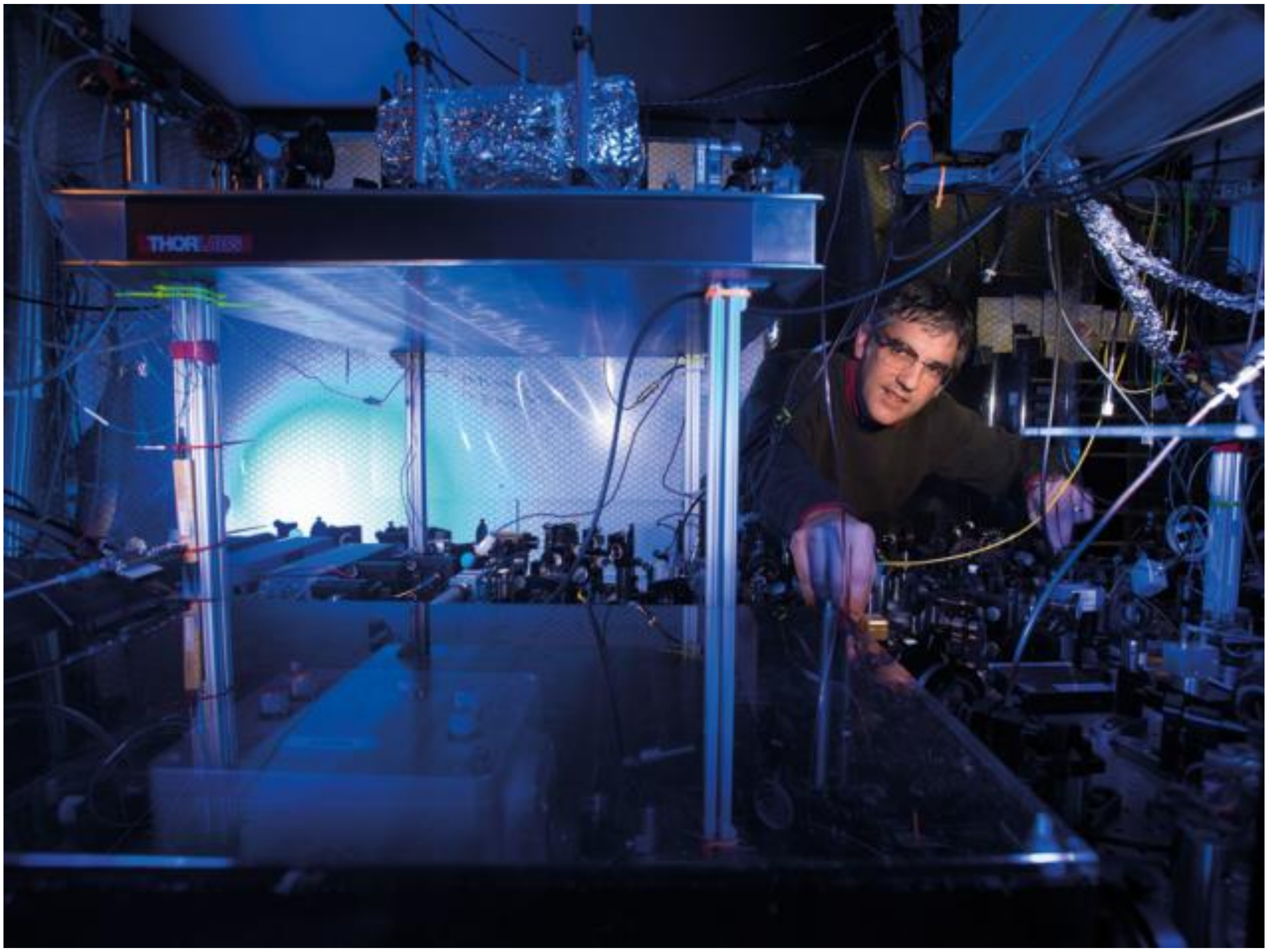
2 First signs

Those researchers considered chains of spins, rather like opened-out versions of Wilczek's ring of interacting quantum particles. "The authors didn't notice the connection to Wilczek's time-crystal discussion," says Huse, but that was soon pointed out by others – specifically by Chetan Nayak of Microsoft Research in Santa Barbara and co-workers (*Phys. Rev. Lett.* **117** 090402), who also proposed how they might be created (figure 2). Yao and colleagues subsequently dubbed these non-equilibrium states "discrete time crystals", or DTCs (*Phys. Rev. Lett.* **118** 030401). The "discrete" comes from the fact that their periodicity is a discrete, integer multiple of the driving period.

Discrete time crystals are very subtle. These systems look like they're in equilibrium, but they're not really

Chris Monroe, University of Maryland

Despite the reservations of Watanabe and Oshikawa, there is something odd about DTCs in Floquet systems that makes them different from chemical waves or other periodic non-equilibrium states. Although they are being energetically driven, they don't actually absorb and dissipate any of that energy. "It's a very subtle concept," says physicist Chris Monroe of the University of Maryland. "These systems look like they're in equilibrium, but they're not really."



Time in his hands: Chris Monroe at the University of Maryland. (Courtesy: John T Consoli/University)

A local affair

This ability to be driven without absorbing energy arises because the disorder in the system makes the energy states isolated from one another. Unable to exchange energy, the system cannot therefore equilibrate. Instead, it gets trapped or "localized" in a particular non-equilibrium state (*Ann. Rev. Cond. Matt. Phys.* **6** 15). This strange situation, dubbed "many-body localization", goes back to work on disordered systems in the late 1950s by Philip Anderson, who would later go on to win a physics Nobel prize.

Many-body localization, says Huse, arises because of the quantized nature of the energy levels. "If you drive it at a particular frequency, this drive will not be exactly resonant with any energy differences and the system may remain localized and fail to steadily absorb energy from the drive," he says. That's crucial, says Yao, because if the system absorbs energy then it slowly heats up until eventually it's so hot that any possibility of well-ordered phases vanishes.

Such behaviour seemed to require two key ingredients: some disorder among the components, and strong interactions linking their behaviour. That made Monroe think about the kinds of systems in which he specializes: ions held in electromagnetic traps. He and others have manipulated such ions as quantum bits (qubits) for quantum computing, with binary information encoded in their energy levels.

Actually, such systems are rather too perfect, says Monroe: to get DTC behaviour, they needed to inject some disorder in their ion arrays, "making each ion qubit a little different from the others". It's precisely because they could introduce this in a controlled way that the trapped ions seemed such an ideal test-bed for comparing with other disordered Floquet systems in which there is more messy, uncontrolled disorder.

Time crystals in the lab

Last year Monroe and his coworkers reported the characteristic signature of a DTC in an array of 10 ytterbium ions held in a trap, where their spins interact with one another (*Nature* **543** 217). When they drove the system with laser pulses to excite transitions between the spin states of the ions, the spin orientation of each atom in the chain started oscillating with a period that was an integer multiple of the driving period. And, crucially, this response frequency is robust. These are the signs of a DTC, says Monroe. "You drive the system in time in a way that's a bit wobbly, not clean, but it always responds in the same way."

At the same time, a team at Harvard University led by Mikhail Lukin saw another way to create a quantum system with the requisite disorder: it could come from impurities distributed randomly in a diamond crystal lattice. Lukin and colleagues described a DTC made from coupled electron spins present in defects composed of a nitrogen atom next to a vacant lattice site in diamond at room temperature (*Nature* **543** 221). They used microwaves to manipulate and drive the spin states – basically the procedure used for electron spin resonance (ESR) spectroscopy – in a 300 nm-diameter region of a microscopic beam made of diamond. "It was not fully clear if the DTC phase could even exist in our system," says Lukin. "But we discovered experimentally that this phase not only exists, but is also remarkably robust."

We discovered experimentally that discrete time crystals not only exist, but that this phase is also remarkably robust.

Mikhail Lukin, Harvard University

The class of materials that act as DTCs has been recently broadened. Earlier this year Ganesh Sreejith and colleagues from the Indian Institute of Science Education and Research in Pune reported it in the interacting nuclear spins of hydrogen, carbon and silicon atoms in three star-shaped organic molecules in solution, probed by nuclear magnetic resonance (NMR) spectroscopy (*Phys. Rev. Lett.* **120** 180602). Given the previous work on spin resonance in diamond defects, says Sreejith, "NMR systems were in some sense a natural place to look for the same physics".

They saw the tell-tale signature of a DTC phase in the way that the oscillation period of the spins is twice that of the driving pulses. And again, says Sreejith, "the oscillation time period is stable against changes in the pulse properties and other perturbations". These results, he concludes, "indicate that the phenomena can be observed in simpler systems than what has been studied previously".

Crystal catchers: Sean Barrett and colleagues at Yale University. (Courtesy: Michael Marsland/Yale University)

Sean Barrett at Yale University and his colleagues had much the same idea of using NMR, in their case to look at crystals of the salt ammonium dihydrogen phosphate (ADP). When they heard about the earlier experiments last year, Barrett explains, “just by chance we had a nice crystal of ADP already under study in our NMR spectrometer for a completely different purpose, to do with magnetic-resonance imaging of bones”. They have seen DTC behaviour by driving transitions in the phosphorus spins using a sequence of radio-frequency pulses (*Phys. Rev. Lett.* **120** 180603 and *Phys. Rev. B* **97** 184301).

Yao says it’s possible that these NMR systems might prove to be only transient time crystals, since they are expected to eventually relax to thermal equilibrium over long timescales – a process still to be understood. Importantly, however, neither the ADP crystals nor the star-shaped molecules studied by the Pune group have much disorder. “So either many-body localization is a broader phenomenon than previously thought, or it is not required for DTC signatures to be seen,” says Barrett. “I think theorists are working hard to understand what this means.”

This notion of DTCs that don’t depend on disorder is already out there, says Monroe. What you need is merely enough complexity in the interactions. Under certain conditions such a system can never relax to an equilibrium state: a phenomenon called pre-thermalization. Monroe is now seeing if it can be realized with his trapped-ion qubits.

Practical applications

The ability to get such a regular and robust time response out of a disordered system could ultimately point to applications. “In these very messy natural systems with disorder, to have a property emerge that is very stable could point the way to some kind of clock, for example,” Monroe says. Barrett seconds that idea. “The DTC oscillations that all four experiments see is a case where regularly applied pulses make densely packed atoms or spins seem to behave as a synchronized unit,” he says. “If we can understand this behaviour better, then it might be used to improve quantum technologies like atomic clocks.”

If we can understand this behaviour better, then it might be used to improve quantum technologies like atomic clocks.

Sean Barrett, Yale University

It would be poetically satisfying if time crystals were to let us measure time more reliably. But Lukin thinks that DTCs might instead be put to a different use, which is that the quantum states between the coupled particles in these systems are so robustly entangled. That means they not only resist the “decoherence” that usually breaks down such states but are also highly sensitive to perturbations such as magnetic fields. They could therefore be used to make tiny magnetic sensors: the more particles there are in the entangled group, the better the sensitivity. Indeed, Lukin, Yao and their collaborator Soonwon Choi reckon that sensors like this could be made either from nitrogen-vacancy defects in diamond or other defects (such as carbon-13 atoms) in layered materials such as graphene (arXiv:1801.00042).

Yao sees another enticing possible application too. Researchers at Microsoft and elsewhere are currently trying to make qubits for quantum computing from quantum states that are rendered stable by “topological protection”: fundamental geometric constraints on the many-body states that would give rise to robust topological qubits. So far, though, making them demands extremely low temperatures, of the order of millikelvins. But Yao says that Floquet phases of DTCs could offer the same benefits at higher temperatures.

Time traders

In fact, he has an even bolder notion: to make DTCs that aren't quantum mechanical at all, but are governed by classical physics (arXiv:1801.02628). Yao and his coworkers have shown that even in that case, a combination of noise-induced disorder and strong interactions between the components can be enough to induce time-periodic behaviour characteristic of a DTC in a chain of classical particles – balls coupled by springs, say – subject to an oscillatory driving force. Looked at this way, time crystals could have been discovered with the mechanics of the 18th century.

And that's what's really exciting about time crystals, Yao says. They show things are possible that you might never have imagined could be. There have even been suggestions of more exotic structures too, such as time quasicrystals and superfluid time crystals (*Phys. Rev. Lett.* **120** 215301). Given the wealth of such paradoxical and surprising substances, time crystals are surely entirely worthy of their *Doctor Who*style name. [25]

Physicists find signs of a time crystal

Yale physicists have uncovered hints of a time crystal—a form of matter that "ticks" when exposed to an electromagnetic pulse—in the last place they expected: a crystal you might find in a child's toy.

The discovery means there are now new puzzles to solve, in terms of how time crystals form in the first place.

Ordinary crystals such as salt or quartz are examples of three-dimensional, ordered spatial crystals. Their atoms are arranged in a repeating system, something scientists have known for a century.

Time crystals, first identified in 2016, are different. Their atoms spin periodically, first in one direction and then in another, as a pulsating force is used to flip them. That's the "ticking." In addition, the ticking in a time crystal is locked at a particular frequency, even when the pulse flips are imperfect.

Scientists say that understanding time crystals may lead to improvements in atomic clocks, gyroscopes, and magnetometers, as well as aid in building potential quantum technologies. The U.S. Department of Defense recently announced a program to fund more research into time crystal systems.

Yale's new findings are described in a pair of studies, one in *Physical Review Letters* and the other in *Physical Review B*. The studies represent the second known experiment observing a telltale signature for a discrete time crystal (DTC) in a solid. Previous experiments led to a flurry of media attention in the past year.

Yale researchers Jared Rovny, left, Robert Blum, center, and Sean Barrett, right, made the discovery. Credit: Yale University

"We decided to try searching for the DTC signature ourselves," said Yale physics professor Sean Barrett, principal investigator for the two new studies. "My student Jared Rovny had grown monoammonium phosphate (MAP) crystals for a completely different experiment, so we happened to have one in our lab."

MAP crystals are considered so easy to grow that they are sometimes included in crystal growing kits aimed at youngsters. It would be unusual to find a time crystal signature inside a MAP crystal, Barrett explained, because time crystals were thought to form in crystals with more internal "disorder."

The researchers used nuclear magnetic resonance (NMR) to look for a DTC signature—and quickly found it. "Our crystal measurements looked quite striking right off the bat," Barrett said. "Our work suggests that the signature of a DTC could be found, in principle, by looking in a children's crystal growing kit."

Another unexpected thing happened, as well. "We realized that just finding the DTC signature didn't necessarily prove that the system had a quantum memory of how it came to be," said Yale graduate student Robert Blum, a co-author on the studies. "This spurred us to try a time crystal 'echo,' which revealed the hidden coherence, or quantum order, within the system," added Rovny, also a Yale graduate student and lead author of the studies.

Barrett noted that his team's results, combined with previous experiments, "present a puzzle" for theorists trying to understand how time crystals form.

"It's too early to tell what the resolution will be for the current theory of discrete time crystals, but people will be working on this question for at least the next few years," Barrett said. [24]

Tracking mechanisms of crystallization in real time

Researchers at the Interfacial Dynamics in Radioactive Environments and Materials (IDREAM) Energy Frontier Research Center quantified transient penta-coordinated Al3+ species during the crystallization of gibbsite from hydrous aluminum gels in solutions of concentrated sodium hydroxide. The research shows that concentrated electrolytes in solution affect hydrogen bonding, ion interactions, and coordination geometries in currently unpredictable ways.

These mechanistic studies support the development of new process flow sheets to accelerate the processing of radioactive wastes at two Department of Energy sites. Further, the studies may provide less energy-intensive routes for industrial aluminum production.

Gibbsite (α-Al(OH)3) is an important mineral resource for industrial aluminum production. It is also present in large quantities in the high-level radioactive waste tanks at U.S. Department of Energy sites in Washington state and South Carolina. Traditional processing for either aluminum production or radioactive waste treatment is an energy-intensive activity. Processing involves heating to facilitate dissolution of gibbsite in highly alkaline solutions of concentrated electrolytes. Heating is followed by cooling to encourage precipitation from these chemically extreme systems.

For radioactive waste treatment, the dissolution and precipitation steps are often quite slow. Why? In part, both processes involve changes in the coordination geometry of the trivalent aluminum. In the solid phase, it is six coordinate to give an octahedral geometry. To move into the solution phase, the aluminum ion must change its geometry to a four-coordinate tetrahedral form.

Led by Jian Zhi Hu and Kevin Rosso, the team conducted high-field magic angle spinning nuclear magnetic resonance spectroscopy studies that probed ion interactions, solute organization, and solvent properties during gibbsite precipitation. The team captured real-time system dynamics as a function of experimental conditions, revealing previously unknown mechanistic details.

The team's work shows that the change in coordination is not a simple transition between the tetrahedral to octahedral species. The change involves an intermediate penta-coordinated aluminum metal center. Further, these species are influenced by subtle changes in solute and solvent organization. These changes lead to gel networks that can sometimes facilitate formation or dissolution of the solid phase. Understanding how aluminum coordination changes in extreme environments may lead to efficiencies in aluminum production and accelerate radioactive waste processing. [23]

The quantum states on the surface of conducting materials can strongly interact with light

An exotic state of matter that is dazzling scientists with its electrical properties, can also exhibit unusual optical properties, as shown in a theoretical study by researchers at A*STAR.

Atomically thin materials, such as graphene, derive some of their properties from the fact that electrons are confined to traveling in just two-dimensions. Similar phenomena are also seen in some three-dimensional materials, in which electrons confined to the surface behave very differently from those within the bulk—for example, topological insulators, whose surface electrons conduct electricity even though their bulk electrons do not. Recently, another exciting class of materials has been identified: the topological semimetal.

The difference in insulator and conductor electrical properties is down to the bandgap: a gap between the ranges, or bands, of energy that an electron traveling through the material can assume. In an insulator, the lower band is full of electrons and the bandgap is too large to enable a current to flow. In a semimetal, the lower band is also full but the lower and upper bands touch at some points, enabling the flow of a small current.

This lack of a full bandgap means that topological semimetals should theoretically exhibit very different properties from those of the more conventional topological insulators.

To prove this, Li-kun Shi and Justin Song from the A*STAR Institute of High Performance Computing used an 'effective Hamiltonian' approximation to show that the two-dimensional surface states in semimetals, known as Fermi arcs, possess a light–matter interaction much stronger than that found in other gapless two-dimensional systems, such as graphene.

"Typically, the bulk dominates material absorption," explains Song. "But we show that Dirac semimetals are unusual in that they possess a very optically active surface due to these peculiar Fermi arc states."

Shi and Song analyzed a proto-typical semimetal with a symmetric band structure where the electronic bands touch at two places, known as Dirac points, and predicted the strength with which incident radiation induces electron transitions from the lower band to the upper one. They found that surface absorption depends heavily on the polarization of light, being 100 to 1,000 times stronger when light is polarized perpendicular—rather than parallel—to the crystal's rotational axis. This strong anisotropy offers a way of optically investigating and probing the topological surfaces states of Dirac semimetals.

"Our goal is to identify more unconventional optics that arise due to Fermi arcs," says Song. "Topological semimetals could host unusual opto-electronic behavior that goes beyond conventional materials." [22]

Breakthrough in circuit design makes electronics more resistant to damage and defects

People are growing increasingly dependent on their mobile phones, tablets and other portable devices that help them navigate daily life. But these gadgets are prone to failure, often caused by small defects in their complex electronics, which can result from regular use. Now, a paper in today's *Nature Electronics* details an innovation from researchers at the Advanced Science Research Center (ASRC) at The Graduate Center of The City University of New York that provides robust protection against circuitry damage that affects signal transmission.

The breakthrough was made in the lab of Andrea Alù, director of the ASRC's Photonics Initiative. Alù and his colleagues from The City College of New York, University of Texas at Austin and Tel Aviv University were inspired by the seminal work of three British researchers who won the 2016 Noble Prize in Physics for their work, which teased out that particular properties of matter (such as electrical conductivity) can be preserved in certain materials despite continuous changes in the matter's form or shape. This concept is associated with topology—a branch of mathematics that studies the properties of space that are preserved under continuous deformations.

"In the past few years there has been a strong interest in translating this concept of matter topology from material science to light propagation," said Alù. "We achieved two goals with this project: First, we showed that we can use the science of topology to facilitate robust electromagnetic-wave propagation in electronics and circuit components. Second, we showed that the inherent robustness associated with these topological phenomena can be self-induced by the signal traveling in the circuit, and that we can achieve this robustness using suitably tailored nonlinearities in circuit arrays."

To achieve their goals, the team used nonlinear resonators to mold a band-diagram of the circuit array. The array was designed so that a change in signal intensity could induce a change in the band diagram's topology. For low signal intensities, the electronic circuit was designed to support a trivial topology, and therefore provide no protection from defects. In this case, as defects were introduced into the array, the signal transmission and the functionality of the circuit were negatively affected.

As the voltage was increased beyond a specific threshold, however, the band-diagram's topology was automatically modified, and the signal transmission was not impeded by arbitrary defects introduced across the circuit array. This provided direct evidence of a topological transition in the circuitry that translated into a self-induced robustness against defects and disorder.

"As soon as we applied the higher-voltage signal, the system reconfigured itself, inducing a topology that propagated across the entire chain of resonators allowing the signal to transmit without any problem," said A. Khanikaev, professor at The City College of New York and co-author in the study. "Because the system is nonlinear, it's able to undergo an unusual transition that makes signal transmission robust even when there are defects or damage to the circuitry."

"These ideas open up exciting opportunities for inherently robust electronics and show how complex concepts in mathematics, like the one of topology, can have real-life impact on common electronic devices," said Yakir Hadad, lead author and former postdoc in Alù's group, currently a professor at Tel-Aviv University, Israel. "Similar ideas can be applied to nonlinear optical circuits and extended to two and three-dimensional nonlinear metamaterials." [21]

Researchers develop heat switch for electronics

Researchers at the University of Illinois at Urbana-Champaign have developed a new technology for switching heat flows 'on' or 'off'. The findings were published in the article "Millimeter-scale liquid metal droplet thermal switch," which appeared in *Applied Physics Letters*.

Switches are used to control many technical products and engineered systems. Mechanical switches are used to lock or unlock doors, or to select gears in a car's transmission system. Electrical switches are used to turn on and off the lights in a room. At a smaller scale, electrical switches in the form of transistors are used to turn electronic devices on and off, or to route logic signals within a circuit.

Engineers have long desired a switch for heat flows, especially in electronics systems where controlling heat flows can significantly improve system performance and reliability. There are however significant challenges in creating such a heat switch.

"Heat flow occurs whenever you have a region of higher temperature near a region of lower temperature," said William King, the Andersen Chair Professor in the Department of Mechanical Science and Engineering and the project co-leader. "In order to control the heat flow, we engineered a specific heat flow path between the hot region and cold region, and then created a way to break the heat flow path when desired."

"The technology is based on the motion of a liquid metal droplet," said Nenad Miljkovic, Assistant Professor in the Department of Mechanical Science and Engineering and the project co-leader. "The metal droplet can be positioned to connect a heat flow path, or moved away from the heat flow path in order to limit the heat flow."

The researchers demonstrated the technology in a system modeled after modern electronics systems. On one side of the switch there was a heat source representing the power electronics component, and on the other side of the switch, there was liquid cooling for heat removal. When the switch was on, they were able to extract heat at more than 10 W/cm2. When the switch was off, the heatflow dropped by nearly 100X.

Besides King and Miljkovic, other authors of the paper include Paul Braun, Racheff Professor of Materials Science and Engineering and the Director of Materials Research Laboratory; and graduate students Tianyu Yang, Beomjin Kwon and Patricia B. Weisensee (now an assistant professor at Washington University in St. Louis) from mechanical science and engineering and Jin Gu Kang and Xuejiao Li from materials science and engineering.

King says that the next step for the research is to integrate the switch with power electronics on a circuit board. The researchers will have a working prototype later this year. [20]

Converting heat into electricity with pencil and paper

Thermoelectric materials can use thermal differences to generate electricity. Now there is an inexpensive and environmentally friendly way of producing them with the simplest tools: a pencil, photocopy paper, and conductive paint. These are sufficient to convert a temperature difference into electricity via the thermoelectric effect, which has now been demonstrated by a team at the Helmholtz-Zentrum Berlin.

The thermoelectric effect was discovered almost 200 years ago by Thomas J. Seebeck. If two metals of different temperatures are brought together, they can develop an electrical voltage. This effect allows residual heat to be converted partially into electrical energy. Residual heat is a by-product of almost all technological and natural processes, such as in power plants and household appliances, not to mention the human body. It is also one of the most under-utilised energy sources in the world.

Tiny effect

However, as useful an effect as it is, it is extremely small in ordinary metals. This is because metals not only have high electrical conductivity, but high thermal conductivity as well, so that differences in temperature disappear immediately. Thermoelectric materials need to have low thermal conductivity despite their high electrical conductivity. Thermoelectric devices made of inorganic semiconductor materials such as bismuth telluride are already being used today in certain technological applications. However, such material systems are expensive and their use only pays off in certain situations. Researchers are exploring whether flexible, nontoxic organic materials based on carbon nanostructures, for example, might also be used in the human body.

The team led by Prof. Norbert Nickel at the HZB has now shown that the effect can be obtained much more simply—using a normal HB-grade pencil, they covered a small area with pencil on ordinary photocopy paper. As a second material, they applied a transparent, conductive co-polymer paint (PEDOT: PSS) to the surface.

The pencil traces on the paper delivered a voltage comparable to other far more expensive nanocomposites that are currently used for flexible thermoelectric elements. And this voltage could be increased tenfold by adding indium selenide to the graphite from the pencil.

The researchers investigated graphite and co-polymer coating films using a scanning electron microscope and Raman scattering at HZB. "The results were very surprising for us as well," says Nickel. "But we have now found an explanation of why this works so well—the pencil deposit left on the paper forms a surface characterised by unordered graphite flakes, some graphene, and clay. While this only slightly reduces the electrical conductivity, heat is transported much less effectively."

These simple constituents might be usable in the future to print extremely inexpensive, environmentally friendly, and non-toxic thermoelectric components onto paper. Such tiny and flexible components could also be used directly on the body and could use body heat to operate small devices or sensors. [19]

A new efficient and portable electrocaloric cooling device

A team of researchers with the University of California and SRI International has developed a new type of cooling device that is both portable and efficient. In their paper published in the journal Science, the team describes their new device and possible applications for its use. Q.M. Zhang and Tian Zhang with the Pennsylvania State University offer some background on electrocaloric theory and outline the work done by the team in California in a Perspectives piece in the same journal issue.

As most everyone knows, conventional air conditioners are bulky, heavy, use a lot of electricity and often leak greenhouse gases into the atmosphere. Thus, conditions are ripe for something new. Some new devices have been developed such as thermoelectric coolers, which make use of ceramics, but they are not efficient enough to play a major role in cooling. A more recent development is the use of devices exploiting the electrocaloric effect, which is where heat moves through certain materials when an electric current is applied. In this new effort, the researchers used a polymer as the material.

The new cooling device was made by layering a polymer between a heat sink and a heat source. Applying electric current to the polymer when it was touching the heat sink caused its molecules to line up, which reduced entropy, forcing heat into the sink. The polymer was then moved into contact with the heat source while the current was turned off. The molecules relaxed, which caused the temperature to drop. Repeating this process resulted in cooling.

The researchers report that the device is extremely efficient, portable and configurable. They suggest the same technology could be used to create coolers for a chair or hat, for example, or perhaps to chill smartphone batteries. They proved this last claim by actually building such a device and using it to cool down a battery heated by ordinary use—after only five seconds, the temperature of the battery had lessened by 8° C. Comparatively, air cooling the battery reduced its temperature just 3° C in 50 seconds. [18]

Fast heat flows in warm, dense aluminum

Thermal conductivity is one of the most crucial physical properties of matter when it comes to understanding heat transport, hydrodynamic evolution and energy balance in systems ranging from astrophysical objects to fusion plasmas.

In the warm dense matter (WDM) regime, experimental data are very rare, so many theoretical models remain untested.

But LLNL researchers have tested theory by developing a platform called "differential heating" to conduct thermal conductivity measurements. Just as land and water on Earth heat up differently in sunlight, a temperature gradient can be induced between two different materials. The subsequent heat flow from the hotter material to the cooler material is detected by time-resolved diagnostics to determine thermal conductivity.

In an experiment using the Titan laser at the Lab's Jupiter Laser Facility, LLNL researchers and collaborators achieved the first measurements of thermal conductivity of warm dense aluminum—a prototype material commonly used in model development—by heating a dual-layer target of gold and aluminum with laser-generated protons.

"Two simultaneous time-resolved diagnostics provided excellent data for gold, the hotter material, and aluminum, the colder material," said Andrew Mckelvey, a graduate student from the University of Michigan and the first author of a paper appearing in Scientific Reports . "The systematic data sets can constrain both the release equation of state (EOS) and thermal conductivity."

By comparing the data with simulations using five existing thermal conductivity models, the team found that only two agree with the data. The most commonly used model in WDM, called the LeeMore model, did not agree with data. "I am glad to see that Purgatorio, an LLNL-based model, agrees with the data," said Phil Sterne, LLNL co-author and the group leader of EOS development and application group in the Physics Division. "This is the first time these thermal conductivity models of aluminum have been tested in the WDM regime."

"Discrepancy still exists at early time up to 15 picoseconds," said Elijah Kemp, who is responsible for the simulation efforts. "This is likely due to non-equilibrium conditions, another active research area in WDM."

The team is led by Yuan Ping through her early career project funded by the Department of Energy Office of Fusion Energy Science Early Career Program. "This platform can be applied to many pairs of materials and by various heating methods including particle and X-ray heating," Ping said. [17]

Controlling heat and particle currents in nanodevices by quantum observation

Researchers from the Theory Department of the MPSD have realized the control of thermal and electrical currents in nanoscale devices by means of quantum local observations.

Measurement plays a fundamental role in quantum mechanics. The best-known illustration of the principles of superposition and entanglement is Schrödinger's cat. Invisible from the outside, the cat resides in a coherent superposition of two states, alive and dead at the same time.

By means of a measurement, this superposition collapses to a concrete state. The cat is now either dead or alive. In this famous thought experiment, a measurement of the "quantum cat" can be seen as an interaction with a macroscopic object collapsing the superposition onto a concrete state by destroying its coherence.

In their new article published in npj Quantum Materials, researchers from the Max Planck Institute for the Structure and Dynamics of Matter and collaborators from the University of the Basque Country (UPV/EHU) and the Bremen Center for Computational Materials Science discovered how a microscopic quantum observer is able to control thermal and electrical currents in nanoscale devices. Local quantum observation of a system can induce continuous and dynamic changes in its quantum coherence, which allows better control of particle and energy currents in nanoscale systems.

Classical non-equilibrium thermodynamics was developed to understand the flow of particles and energy between multiple heat and particle reservoirs. The best-known example is Clausius' formulation of the second law of thermodynamics, stating that when two objects with different temperatures are brought in contact, heat will exclusively flow from the hotter to the colder one.

In macroscopic objects, the observation of this process does not influence the flow of energy and particles between them. However, in quantum devices, thermodynamical concepts need to be revisited. When a classical observer measures a quantum system, this interaction destroys most of the coherence inside the system and alters its dynamical response.

Instead, if a quantum observer acts only locally, the system quantum coherence changes continuously and dynamically, thus providing another level of control of its properties. Depending on how strong and where these local quantum observations are performed, novel and surprising quantum transport phenomena arise.

The group of Prof.Dr. Angel Rubio at the Theory Department of the MPSD, along with their colleagues, have demonstrated how the concept of quantum measurements can offer novel possibilities for a thermodynamical control of quantum transport (heat and particle). This concept offers possibilities far beyond those obtained using standard classical thermal reservoirs.

The scientists studied this idea in a theoretical quantum ratchet. Within this system, the left and right side are connected to hot and cold thermal baths, respectively. This configuration forces the energy to flow from hot to cold and the particles to flow clockwise inside the ratchet. The introduction of a quantum observer, however, inverts the particle ring-current against the natural direction of the ratchet—a phenomenon caused by the localized electronic state and the disruption of the system's symmetry.

Furthermore, the quantum observation is also able to invert the direction of the heat flow, contradicting the second law of thermodynamics. "Such heat and particle current control might open the door for different strategies to design quantum transport devices with directionality control of the injection of currents. There could be applications in thermoelectricity, spintronics, photonics, and sensing, among others. These results have been an important contribution to my PhD thesis," says Robert Biele, first author of the paper.

From a more fundamental point of view, this work highlights the role of a quantum observer. In contrast to Schrödinger's cat, where the coherent state is destroyed via the interaction with a macroscopic "observer," here, by introducing a local quantum observer, the coherence is changed locally and dynamically, allowing researchers to tune between the coherent states of the system. "This shows how thermodynamics is very different in the quantum regime. Schrödinger's cat paradox leads to new thermodynamic forces never seen before," says César A. Rodríguez Rosario.

In the near future, the researchers will apply this concept to control spins for applications in spin injection and novel magnetic memories. Angel Rubio suggests that "The quantum observer—besides controlling the particle and energy transfer at the nanoscale—could also observe spins, select individual components, and give rise to spin-polarized currents without spin-orbit coupling. Observation could be used to write a magnetic memory." [16]

Maxwell's demon extracts work from quantum measurement

Physicists have proposed a new type of Maxwell's demon—the hypothetical agent that extracts work from a system by decreasing the system's entropy—in which the demon can extract work just by making a measurement, by taking advantage of quantum fluctuations and quantum superposition.

The team of Alexia Auffèves at CNRS and Université Grenoble Alpes have published a paper on the new Maxwell's demon in a recent issue of Physical Review Letters.

"In the classical world, thermodynamics teaches us how to extract energy from thermal fluctuations induced on a large system (such as a gas or water) by coupling it to a hot source," Auffèves told Phys.org. "In the quantum world, the systems are small, and they can fluctuate—even if they are not hot, but simply because they are measured. In our paper, we show that it is possible to extract energy from these genuinely quantum fluctuations, induced by quantum measurement."

In the years since James Clerk Maxwell proposed the first demon around 1870, many other versions have been theoretically and experimentally investigated. Most recently, physicists have begun investigating Maxwell's demons that operate in the quantum regime, which could one day have implications for quantum information technologies.

Most quantum versions of the demon have a couple things in common: They are thermally driven by a heat bath, and the demon makes measurements to extract information only. The measurements do not actually extract any work, but rather the information gained by the measurements allows the demon to act on the system so that energy is always extracted from the cycle.

The new Maxwell's demon differs from previous versions in that there is no heat bath—the demon is not thermally driven, but measurement-driven. Also, the measurements have multiple purposes: They not only extract information about the state of the system, but they are also the "fuel" for extracting work from the system. This is because, when the demon performs a measurement on a qubit in the proposed system, the measurement projects the qubit from one state into a superposition of states, which provides energy to the qubit simply due to the measurement process. In their paper, the physicists proposed an experiment in which projective quantum non-demolition measurements can be performed with light pulses repeated every 70 nanoseconds or so.

Since recent experiments have already demonstrated the possibility of performing measurements at such high frequencies, the physicists expect that the new Maxwell's demon could be readily implemented using existing technology. In the future, they also plan to investigate potential applications for quantum computing.

"This engine is a perfect proof of concept evidencing that quantum measurement has some energetic footprint," Auffèves said. "Now I would like to reverse the game and use this effect to estimate the energetic cost of quantum tasks, if they are performed in the presence of some measuring entity. This is the case in a quantum computer, which is continuously 'measured' by its surroundings. This effect is called decoherence and is the biggest enemy of quantum computation. Our work provides tools to estimate the energy needed to counteract it." [15]

Physicists read Maxwell's Demon's mind

Pioneering research offers a fascinating view into the inner workings of the mind of 'Maxwell's Demon', a famous thought experiment in physics.

An international research team, including Dr Janet Anders from the University of Exeter, have used superconducting circuits to bring the 'demon' to life.

The demon, first proposed by James Clerk Maxwell in 1867, is a hypothetical being that can gain more useful energy from a thermodynamic system than one of the most fundamental laws of physics—the second law of thermodynamics—should allow.

Crucially, the team not only directly observed the gained energy for the first time, they also tracked how information gets stored in the demon's memory.

The research is published in the leading scientific journal Proceedings of the National Academy of Sciences (PNAS).

The original thought experiment was first proposed by mathematical physicist James Clerk Maxwell—one of the most influential scientists in history—150 years ago.

He hypothesised that gas particles in two adjacent boxes could be filtered by a 'demon' operating a tiny door, that allowed only fast energy particles to pass in one direction and low energy particles the opposite way.

As a result, one box gains a higher average energy than the other, which creates a pressure difference. This non-equilibrium situation can be used to gain energy, not unlike the energy obtained when water stored behind a dam is released.

So although the gas was initially in equilibrium, the demon can create a non-equilibrium situation and extract energy, bypassing the second law of thermodynamics.

Dr Anders, a leading theoretical physicist from the University of Exeter's physics department adds: "In the 1980s it was discovered that this is not the full story. The information about the particles' properties remains stored in the memory of the demon. This information leads to an energetic cost which then reduces the demon's energy gain to null, resolving the paradox."

In this research, the team created a quantum Maxwell demon, manifested as a microwave cavity, that draws energy from a superconducting qubit. The team was able to fully map out the memory of the demon after its intervention, unveiling the stored information about the qubit state.

Dr Anders adds: "The fact that the system behaves quantum mechanically means that the particle can have a high and low energy at the same time, not only either of these choices as considered by Maxwell."

This ground-breaking experiment gives a fascinating peek into the interplay between quantum information and thermodynamics, and is an important step in the current development of a theory for nanoscale thermodynamic processes.

'Observing a Quantum Maxwell demon at Work' is published in PNAS. [14]

Researchers posit way to locally circumvent Second Law of Thermodynamics

For more than a century and a half of physics, the Second Law of Thermodynamics, which states that entropy always increases, has been as close to inviolable as any law we know. In this universe, chaos reigns supreme.

But researchers with the U.S. Department of Energy's (DOE's) Argonne National Laboratory announced recently that they may have discovered a little loophole in this famous maxim.

Their research, published in Scientific Reports, lays out a possible avenue to a situation where the Second Law is violated on the microscopic level.

The Second Law is underpinned by what is called the H-theorem, which says that if you open a door between two rooms, one hot and one cold, they will eventually settle into lukewarm equilibrium; the hot room will never end up hotter.

But even in the twentieth century, as our knowledge of quantum mechanics advanced, we didn't fully understand the fundamental physical origins of the H-theorem.

Recent advancements in a field called quantum information theory offered a mathematical construction in which entropy increases.

"What we did was formulate how these beautiful abstract mathematical theories could be connected to our crude reality," said Valerii Vinokur, an Argonne Distinguished Fellow and corresponding author on the study.

The scientists took quantum information theory, which is based on abstract mathematical systems, and applied it to condensed matter physics, a well-explored field with many known laws and experiments.

"This allowed us to formulate the quantum H-theorem as it related to things that could be physically observed," said Ivan Sadovskyy, a joint appointee with Argonne's Materials Science Division and the Computation Institute and another author on the paper. "It establishes a connection between welldocumented quantum physics processes and the theoretical quantum channels that make up quantum information theory."

The work predicts certain conditions under which the H-theorem might be violated and entropy—in the short term—might actually decrease.

As far back as 1867, physicist James Clerk Maxwell described a hypothetical way to violate the Second Law: if a small theoretical being sat at the door between the hot and cold rooms and only let through particles traveling at a certain speed. This theoretical imp is called "Maxwell's demon."

"Although the violation is only on the local scale, the implications are far-reaching," Vinokur said. "This provides us a platform for the practical realization of a quantum Maxwell's demon, which could make possible a local quantum perpetual motion machine."

For example, he said, the principle could be designed into a "refrigerator" which could be cooled remotely—that is, the energy expended to cool it could take place anywhere.

The authors are planning to work closely with a team of experimentalists to design a proof-ofconcept system, they said.

The study, "H-theorem in quantum physics," was published September 12 in Nature Scientific Reports. [13]

What is quantum in quantum thermodynamics?

A lot of attention has been given to the differences between the quantum and classical worlds. For example, quantum entanglement, superposition, and teleportation are purely quantum phenomena with no classical counterparts. However, when it comes to certain areas of thermodynamics— specifically, thermal engines and refrigerators—quantum and classical systems so far appear to be nearly identical. It seems that the same thermodynamic laws that govern the engines in our vehicles may also accurately describe the tiniest quantum engines consisting of just a single particle.

In a new study, physicists Raam Uzdin, Amikam Levy, and Ronnie Kosloff at the Hebrew University of Jerusalem have investigated whether there is anything distinctly quantum about thermodynamics at the quantum level, or if "quantum" thermodynamics is really the same as classical thermodynamics.

For the first time, they have shown a difference in the thermodynamics of heat machines on the quantum scale: in part of the quantum regime, the three main engine types (two-stroke, four-stroke, and continuous) are thermodynamically equivalent. This means that, despite operating in different ways, all three types of engines exhibit all of the same thermodynamic properties, including generating the same amounts of power and heat, and doing so at the same efficiency. This new "thermodynamical equivalence principle" is purely quantum, as it depends on quantum effects, and does not occur at the classical level.

The scientists also showed that, in this quantum regime where all engines are thermodynamically equivalent, it's possible to extract a quantum-thermodynamic signature that further confirms the presence of quantum effects. They did this by calculating an upper limit on the work output of a classical engine, so that any engine that surpasses this bound must be using a quantum effect—namely, quantum coherence—to generate the additional work. In this study, quantum coherence, which accounts for the wave-like properties of quantum particles, is shown to be critical for power generation at very fast engine cycles.

"To the best of my knowledge, this is the first time [that a difference between quantum and classical thermodynamics has been shown] in heat machines," Uzdin told Phys.org. "What has been surprising [in the past] is that the classical description has still held at the quantum level, as many authors have shown. The reasons are now understood, and in the face of this classicality, people have started to stray to other types of research, as it was believed that nothing quantum can pop up.

Thus, it was very difficult to isolate a generic effect, not just a numerical simulation of a specific case, with a complementing theory that manages to avoid the classicality and demonstrate quantum effects in thermodynamic quantities, such as work and heat."

One important implication of the new results is that quantum effects may significantly increase the performance of engines at the quantum level. While the current work deals with single-particle engines, the researchers expect that quantum effects may also emerge in multi-particle engines, where quantum entanglement between particles may play a role similar to that of coherence. [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 nonequilibrium 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

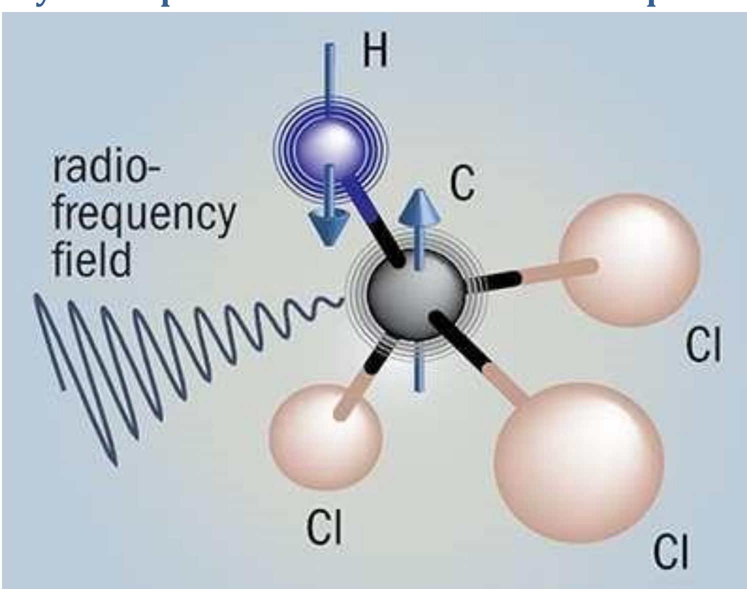


Diagram showing the spin of a carbon atom in a chloroform molecule

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 $\boldsymbol{E = hv}$ and $\boldsymbol{E = mc^2}$, $\boldsymbol{m = hv / c^2}$ that is the $\boldsymbol{m}$ depends only on the $\boldsymbol{v}$ 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 $\boldsymbol{m_o}$ 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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