Tests of Bell's Inequality

In numerous previous experiments, physicists have observed correlations between particles in excess of the limit set by Bell's inequality, which suggests that they are indeed entangled, just as predicted by quantum theory. But each such test has been subject to various "loopholes," scenarios that might account for the observed correlations even if the world were not governed by quantum mechanics. [11]

Using a Bose-Einstein condensate composed of millions of sodium atoms, researchers at the Georgia Institute of Technology have observed a sharp magnetically-induced quantum phase transition where they expect to find entangled atomic pairs. The work moves scientists closer to an elusive entangled state that would have potential sensing and computing applications beyond its basic science interests. [10]

A team of researchers at the University of Cambridge has succeeded in creating turbulence in a Bose–Einstein condensate (BEC) and in the process, have possibly opened the door to a new avenue of research. In their paper published in the journal Nature, the team describes how they achieved this feat and the evidence they found for a cascade. Brian Anderson with the University of Arizona offers a News & Views piece describing the work done by the team in the same journal issue and offers a brief overview of the characteristic distribution of kinetic energy in turbulent fluids. [9]

Bose-Einstein condensates (BECs) are macroscopic systems that have quantum behaviour, and are useful for exploring fundamental physics. Now researchers at the Gakushuin University and the University of Electro-Communications have studied how the miscibility of multicomponent BECs affects their behaviour, with surprising results. [8]

Particles can be classified as bosons or fermions. A defining characteristic of a boson is its ability to pile into a single quantum state with other bosons. Fermions are not allowed to do this. One broad impact of fermionic anti-social behavior is that it allows for carbon-based life forms, like us, to exist. If the universe were solely made from bosons, life would certainly not look like it does. Recently, JQI theorists have proposed an elegant method for achieving transmutation—that is, making bosons act like fermions. This work was published in the journal Physical Review Letters. [7]

Quantum physics tell us that even massive particles can behave like waves, as if they could be in several places at once. This phenomenon is typically proven *in the diffraction of a matter wave at a grating. Researchers have now carried this idea to the extreme and observed the delocalization of molecules at the thinnest possible grating, a mask milled into a single layer of atoms. [6]*

Researchers in Austria have made what they call the "fattest Schrödinger cats realized to date". They have demonstrated quantum superposition – in which an object exists in two or more states simultaneously – for molecules composed of up to 430 atoms each, several times larger than molecules used in previous such experiments1. [5]

Patrick Coles, Jedrzej Kaniewski, and Stephanie Wehner made the breakthrough while at the Centre for Quantum Technologies at the National University of Singapore. They found that 'wave-particle duality' is simply the quantum 'uncertainty principle' in disguise, reducing two mysteries to one. [4]

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.

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Author: George Rajna

Preface

"The connection between uncertainty and wave-particle duality comes out very naturally when you consider them as questions about what information you can gain about a system. Our result highlights the power of thinking about physics from the perspective of information," says Wehner, who is now an Associate Professor at QuTech at the Delft University of Technology in the Netherlands. [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.

Physicists address loophole in tests of Bell's inequality using 600-year-old starlight

Quantum entanglement may appear to be closer to science fiction than anything in our physical reality. But according to the laws of quantum mechanics—a branch of physics that describes the world at the scale of atoms and subatomic particles—quantum entanglement, which Einstein once skeptically viewed as "spooky action at a distance," is, in fact, real.

Imagine two specks of dust at opposite ends of the universe, separated by several billion light years. Quantum theory predicts that, regardless of the vast distance separating them, these two particles can be entangled. That is, any measurement made on one will instantaneously convey information about the outcome of a future measurement on its partner. In that case, the outcomes of measurements on each member of the pair can become highly correlated.

If, instead, the universe behaves as Einstein imagined it should—with particles having their own, definite properties prior to measurement, and with local causes only capable of yielding local effects—then there should be an upper limit to the degree to which measurements on each member of the pair of particles could be correlated. Physicist John Bell quantified that upper limit, now known as "Bell's inequality," more than 50 years ago.

In numerous previous experiments, physicists have observed correlations between particles in excess of the limit set by Bell's inequality, which suggests that they are indeed entangled, just as predicted by quantum theory. But each such test has been subject to various "loopholes," scenarios that might account for the observed correlations even if the world were not governed by quantum mechanics.

Now, physicists from MIT, the University of Vienna, and elsewhere have addressed a loophole in tests of Bell's inequality, known as the freedom-of-choice loophole, and have presented a strong demonstration of quantum entanglement even when the vulnerability to this loophole is significantly restricted.

"The real estate left over for the skeptics of quantum mechanics has shrunk considerably," says David Kaiser, the Germeshausen Professor of the History of Science and professor of physics at MIT. "We haven't gotten rid of it, but we've shrunk it down by 16 orders of magnitude."

A research team including Kaiser; Alan Guth, the Victor F. Weisskopf Professor of Physics at MIT; Andrew Friedman, an MIT research associate; and colleagues from

the University of Vienna and elsewhere has published its results today in the journal Physical Review Letters.

Closing the door on quantum alternatives

The freedom-of-choice loophole refers to the idea that experimenters have total freedom in choosing their experimental setup, from the types of particles to entangle, to the measurements they choose to make on those particles. But what if there were some other factors or hidden variables correlated with the experimental setup, making the results appear to be quantumly entangled, when in fact they were the result of some nonquantum mechanism?

Physicists have attempted to address this loophole with extremely controlled experiments, in which they produce a pair of entangled photons from a single source, then send the photons to two different detectors and measure properties of each photon to determine their degree of correlation, or entanglement. To rule out the possibility that hidden variables may have influenced the results, researchers have used random number generators at each detector to decide what property of each photon to measure, in the split second between when the photon leaves the source and arrives at the detector.

But there is a chance, however slight, that hidden variables, or nonquantum influences, may affect a random number generator before it relays its split-second decision to the photon detector.

"At the heart of quantum entanglement is the high degree of correlations in the outcomes of measurements on these pairs [of particles]," Kaiser says. "But what if a skeptic or critic insisted these correlations weren't due to these particles acting in a fully quantum mechanical way? We want to address whether there is any other way that those correlations could have snuck in without our having noticed."

"Stars aligned"

In 2014, Kaiser, Friedman, and their colleague Jason Gallicchio (now a professor at Harvey Mudd College) proposed an experiment to use ancient photons from astronomical sources such as stars or quasars as "cosmic setting generators," rather than random number generators on Earth, to determine the measurements to be made on each entangled photon. Such cosmic light would be arriving at Earth from objects that are very far away—anywhere from dozens to billions of light years away. Thus, if some hidden variables were to interfere with the randomness of the choice of measurements, they would have had to have set those changes in motion before the time the light left the cosmic source, long before the experiment on Earth was conducted.

In this new paper, the researchers have demonstrated their idea experimentally for the first time. The team, including Professor Anton Zeilinger and his group at the

University of Vienna and the Austrian Academy of Sciences, set up a source to produce highly entangled pairs of photons on the roof of a university laboratory in Vienna. In each experimental run, they shot the entangled photons out in opposite directions, toward detectors located in buildings several city blocks away—the Austrian National Bank and a second university building.

The researchers also set up telescopes at both detector sites and trained them on stars, the closest of which is about 600 light years away, which they had previously determined would send sufficient photons, or starlight, in their direction.

"On those nights, the stars aligned," Friedman says. "And with bright stars like these, the number of photons coming in can be like a firehose. So we have these very fast detectors that can register detections of cosmic photons on subnanosecond timescales."

"Out of whack" with Einstein

In the few microseconds before an entangled photon arrived at a detector, the researchers used each telescope to rapidly measure a property of an incoming stellar photon—in this case, whether its wavelength was redder or bluer than a particular reference wavelength. They then used this random property of the stellar photon, generated 600 years ago by its star, to determine what property of the incoming entangled photons to measure. In this case, red stellar photons signaled a detector to measure an entangled photon's polarization in a particular direction. A blue stellar photon would set the device to measure the polarization of the entangled particle along a different direction.

The team conducted two experiments, with each experimental run lasting only three minutes. In each case, the researchers measured about 100,000 pairs of entangled photons. They found that the polarization measurements of the photon pairs were highly correlated, well in excess of the bound set by Bell's inequality, in a way that is most easily explained by quantum mechanics.

"We find answers consistent with quantum mechanics to an enormously strong degree, and enormously out of whack with an Einstein-like prediction," Kaiser says.

The results represent improvements by 16 orders of magnitude over previous efforts to address the freedom-of-choice loophole.

"All previous experiments could have been subject to this weird loophole to account for the results microseconds before each experiment, versus our 600 years," Kaiser says. "So it's a difference of a millionth of a second versus 600 years' worth of seconds—16 orders of magnitude."

"This experiment pushes back the latest time at which the conspiracy could have started," Guth adds. "We're saying, in order for some crazy mechanism to simulate

quantum mechanics in our experiment, that mechanism had to have been in place 600 years ago to plan for our doing the experiment here today, and to have sent photons of just the right messages to end up reproducing the results of quantum mechanics. So it's very far-fetched."

There is also a second, equally far-fetched possibility, says Michael Hall, a senior research fellow at Griffith University in Brisbane, Australia.

"When photons from the distant stars reach the devices that determine the measurement settings, it is possible that these devices act in some way to change the colors of the photons, in a way that is correlated with the laser producing the entanglement," says Hall, who was not involved in the work. "This would only require a 10-microsecond-old conspiracy between the devices and the laser. However, the idea that photons don't show their 'true colors' when detected would overturn all observational astronomy and basic electromagnetism." [11]

Looking for entangled atoms in a Bose-Einstein condensate

Using a Bose-Einstein condensate composed of millions of sodium atoms, researchers at the Georgia Institute of Technology have observed a sharp magnetically-induced quantum phase transition where they expect to find entangled atomic pairs. The work moves scientists closer to an elusive entangled state that would have potential sensing and computing applications beyond its basic science interests.

The use of entangled atoms from a condensate could improve the sensitivity and reduce the noise in sensing very small changes in physical properties such as magnetic fields or rotation. And it could also provide a foundation for quantum computers able to perform certain calculations much faster than conventional digital computers.

Sponsored by the National Science Foundation, the research was reported January 23 as a rapid communication in the journal Physical Review A.

"We have defined a window where we expect to be able to observe entanglement," said Chandra Raman, an associate professor in the Georgia Tech School of Physics. "We now know where to look for it, and we know how to look for it."

Raman and former graduate student Anshuman Vinit have been studying Bose-Einstein condensates (BECs) as a source of entanglement, seeking to take advantage of the system's quantum purity to create conditions where correlation between atoms might occur. BECs don't normally contain entangled atoms.

"We found ways to engineer the system to create entanglement," Raman explained. "We looked at the behavior of the system as we tuned the magnetic field very close to the phase boundary and showed that the boundary had a very sharply defined point. We were able to resolve that boundary with a level of uncertainty we didn't think we could get until we did the experiment."

Theoretical predictions have suggested that at the boundary between different magnetic phases of a spinor Bose-Einstein condensate, scientists would find an entangled quantum state of all the atoms. In spinor Bose-Einstein condensates, the individual magnetic moments do not need to have a well-defined orientation in space, but rather, can exist in a superposition of different orientations.

In their experiment, the researchers identified two phases: antiferromagnetic and polar. In the polar phase, the atoms all align their moments vertically, while in the antiferromagnetic phase, they are horizontally aligned. In a BEC exactly at the boundary between these phases, theorists had predicted the existence of a quantum mechanical superposition of all possible alignments, an entangled state.

The researchers haven't yet observed that entangled state yet, but their work so far has defined an experimental window within which to look for new physical effects governing different magnetic phases, or to generate entangled states that are relevant for quantum-based systems.

Earlier research in Raman's lab had produced the two phases, but the boundary between them was "smeared out" by magnetic field inhomogeneities. By smoothing out the magnetic field so that it was more uniform, the researchers were able to eliminate the variations to produce a sharp boundary between the phases.

In the narrowly-defined transition area identified in the research, atoms are torn between the two phases, causing entangled pairs to form, Raman said. The state may be stable enough to find practical applications, though scientists won't know for sure until they actually can observe and measure the properties.

The researchers measured the boundary in their system by "jumping" the magnetic field from one part of the BEC to another. The move created a dynamical instability in the atomic system; the larger the instability, the less time the system required to return to equilibrium, as predicted by quantum theory.

The researchers now believe they've set the stage for observing entanglement in a smaller groups of atoms, perhaps no more than a thousand.

"At our current sensitivity, we think we could observe these spin-correlated states with a reasonable number of particles," Raman said. "We think that is experimentally feasible, and since we can measure the boundary with precision, we can begin to test the theories governing behavior in this regime."

Once that's shown, the large ensemble of atoms could be broken down into many smaller groups operating independently, each with phase boundaries containing entangled atoms.

Though Raman finds the basic science and quantum computing interesting, he is equally excited about potential sensing applications.

"If you could reduce the noise level through the clever use of quantum mechanical superpositions, you could realize sensors that are more precise and could detect smaller effects," he said. "In quantum sensing you could use entanglement to increase the precision of measurements to levels that, in classical sensor systems, would have a higher noise level."

In classical oscillating systems such as coin tosses, each flip is an independent system and has a certain level of noise. But because of the correlation, the atomic pairs would no longer be independent systems.

"In an ordinary classical system, there's a certain amount of noise that has to do with the fact that you are making measurements on independent systems," he said. "In quantum systems, it is possible to suppress that noise if the atoms are correlated. It's as if the coins were talking to one another."

Quantum sensors might therefore be able to detect changes in rotation or magnetic variation that are too small for today's sensors. Other applications could be found in spectroscopic measurement, Raman said. [10]

Producing turbulence in a Bose-Einstein condensate yields cascade of wave-like excitations

A team of researchers at the University of Cambridge has succeeded in creating turbulence in a Bose–Einstein condensate (BEC) and in the process, have possibly opened the door to a new avenue of research. In their paper published in the journal Nature, the team describes how they achieved this feat and the evidence they found for a cascade. Brian Anderson with the University of Arizona offers a News & Views piece describing the work done by the team in the same journal issue and offers a brief overview of the characteristic distribution of kinetic energy in turbulent fluids.

Scientists have learned a lot about the nature of turbulence in fluids over the past several hundred years, some of which surrounds the way kinetic energy is distributed among components that have different momenta—which can be seen in action, as Anderson notes, by stirring cream into a cup of coffee. But until now, no one had succeeded in producing turbulence in a BEC, in which a gas of bosons is cooled to near absolute zero causing them to occupy the lowest possible quantum state, thereby allowing for viewing quantum phenomena—Anderson calls them "microscopic droplets of atomic gasses."

In this new effort, the researchers conducted experiments designed to discover what might happen if turbulence were introduced to a BEC, in this case, one made of rubidium atoms captured in a laser-created virtual box—this type of setup provided uniform density of the atoms. The team then applied a timed magnetic field that served to shake up the cloud of atoms, which added energy to the system. They then determined the momentum distribution. For small time intervals, they found most of the atoms in the cloud were in a low-momentum mode—more shaking pushed the atoms into a higher momentum mode. After approximately two seconds, the researchers found evidence of a cascade of excitations by releasing the cloud and capturing what occurred with a 2-D camera.

The method used by the team to cause the turbulence in a BEC is likely to be used as a model for future experiments involving quantum turbulence. [9]

Bose-Einstein condensates miscibility properties reveal surprises

Bose-Einstein condensates (BECs) are macroscopic systems that have quantum behaviour, and are useful for exploring fundamental physics. Now researchers at the Gakushuin University and the University of Electro-Communications have studied how the miscibility of multicomponent BECs affects their behaviour, with surprising results.

Fundamental particles have a property associated with angular momentum described as spin. Force particles - photons, gluons, and so on - have integer spin values and are called bosons; matter particles - electrons, neutrons, protons, and so on - have half integer values of spin and are called fermions. In composites of several fermions, as in atoms and nuclei, the total spin can be integer values so they can behave as bosons. While identical fermions cannot occupy the same state, bosons can, and if cooled to sufficiently low temperatures they will all occupy the lowest possible energy state - a Bose-Einstein condensate.

The researchers studied a BEC of rubidium atoms exploiting the element's rich spin states. They created optical traps containing around 3 x 105 atoms in two different spin states, and applied magnetic-field gradient pulses to separate condensates with different spins. The miscibility of different components of a BEC is determined by the strength of interactions between and within the atoms, which the researchers could tune to produce miscible and immiscible multicomponent BECs.

After removing the magnetic field they left the system to evolve before releasing from the trap and imaged the resulting condensate distribution. "The various counterintuitive effects such as mutual penetration in immiscible BECs, bouncing between miscible BECs, and domain formation in miscible

BECs were observed," report the researchers. Numerical simulations of the system revealed further insights, showing that "the properties of penetration and bouncing can be tuned by slightly changing the atomic interaction strengths." [8]

Shaking bosons into fermions

This transmutation is an example of emergent behavior, specifically what's known as quasiparticle excitations—one of the concepts that make condensed matter systems so interesting. Particles by themselves have mostly well-defined characteristics, but en masse, can work together such that completely distinctive, even exotic phenomena appear. Typically collective behaviors are difficult to study because the large numbers of real particles and all of their interactions are computationally challenging and in many cases prohibitive. JQI Fellow Victor Galitski explains, "The whole idea of emergent excitations is that the quasiparticles are fundamentally different from the actual individual particles. But this actually doesn't happen that often." In this case, it turns out that the boson-to-fermion transmutation leads to an interesting phase of matter. Galitski continues, " Here, the bosons don't condense—they instead form a state without long-range order. This is an example of a long sought after state of matter called a Bose liquid."

In this research, the authors propose a method for realizing and observing such unusual excitations—here the fermionic quasiparticles. The experiment harnesses the strengths of atom-optical systems, such as using bosons (which are easier to work with), a relatively simple lattice geometry (made from lasers that are the workhorses of atomic physics), and established measurement techniques. Galitski continues, "In some sense this was motivated by an experiment where researchers shook a one-dimensional lattice, and it appears that the experiment we propose here is not beyond the capabilities of current work."

Here, the central technique also involves taking an optical lattice made from laser light and shaking it back-and-forth. An atom-optical lattice system, analogous to a crystal, has a periodic structure. Laser beams criss-cross to form standing waves of light that resemble an egg carton. Atoms interact with the light such that they are drawn to the valleys of the egg carton. Like a true solid, this system has an accompanying band-structure, which describes the allowed energies that atoms within the lattice can take on. Without the lattice present, trapped ultracold bosons form a state of matter called a Bose-Einstein condensate. Not much changes when a typical optical lattice is turned on—the bosons will still collect into the lowest energy state and still be in this condensate form. For the simplest lattice configurations, this state corresponds to a single point on a nearly-flattened parabola in the band structure. This configuration is actually the starting point of many atomic physics experiments. Physicists are interested in modifying the energy bands to perhaps uncover more complex phases of matter. To do this, lattice properties must be altered.

In this work, the authors seek to achieve transmutation, and are among those that have previously shown that one way to accomplish this is to construct a lattice whose band structure looks like a moat. (The word moat here means what it did in medieval times—a trench around a structure.)

Lead author and postdoctoral researcher Tigran Sedrakyan explains the significance of the moat, "The moat is instrumental in achieving this statistical transmutation because it appears that the fermions in a moat-band may actually have lower energy than condensed bosons have, enforcing the constituent bosons to transmute."

It turns out that getting the requisite moat to appear has not been so easy. Surprisingly, in this new work, the team found that if, instead of modifying the lattice geometry itself, they take a simple two-dimensional lattice and shake it back and forth, then a moat appears in what was otherwise an unremarkable, almost flat band structure. The rate of shaking is specially chosen such that the bands undergo this transformation.

The particles themselves do not actually change from bosons to fermions. What's happening is that the environment of the lattice is modifying the bosonic behavior.

When the lattice is quivering periodically at a specially determined frequency, the bosons act as if they are governed by fermionic statistics. In the new band structure, the bosons do not form a condensate. [7]

Quantum diffraction at a breath of nothing

The quantum mechanical wave nature of matter is the basis for a number of modern technologies like high resolution electron microscopy, neutron-based studies on solid state materials or highly sensitive inertial sensors working with atoms. The research in the group around Prof. Markus Arndt at the University of Vienna is focused on how one can extend such technologies to large molecules and cluster.

In order to demonstrate the quantum mechanical nature of a massive object it has to be delocalized first. This is achieved by virtue of Heisenberg's uncertainty relation: If molecules are emitted from a point-like source, they start to 'forget' their position after a while and delocalize. If you place a grating into their way, they cannot know, not even in principle, through which slit they are flying. It is as if they traversed several slits at the same time. This results in a characteristic distribution of particles behind the grating, known as the diffraction or interference pattern. It can only be understood if we take the particles' quantum mechanical wave nature into account.

At the technological limit

In a European collaboration (NANOQUESTFIT) together with partners around Professor Ori Cheshnovsky at Tel Aviv University (where all nanomasks were written), as well as with support by groups in Jena (growth of biphenyl membranes, Prof. Turchanin), and Vienna (High-Resolution Electron Microscopy, Prof. Meyer) they now demonstrated for the first time that such gratings can be fabricated even from the thinnest conceivable membranes. They milled transmission masks into ultra-thin membranes of silicon nitride, biphenyl molecules or carbon with a focussed ion beam and analysed them with ultra-high resolution electron microscopy. The team succeeded in fabricating stable and sufficiently large gratings even in atomically thin single layer graphene.

In previous quantum experiments of the same EU collaboration, the thickness of diffraction masks was already as thin as a hundredth of the diameter of a hair.

However, even such structures were still too thick for the diffraction of molecules composed of dozens of atoms. The same force that allows geckos to climb walls restricts the applicability of material gratings in quantum diffraction experiments: Molecules are attracted to the grating bars like the geckos' toes to the wall.

However, once they stick to the surface they are lost to the experiment. A grand challenge was to reduce the material thickness and thus the attractive interactions of these masks down to the ultimate limit while retaining a mechanically stable structure.

"These are the thinnest possible diffraction masks for matter wave optics. And they do their job very well," says Christian Brand, the lead author of this publication.

"Given the gratings' thickness of a millionth of a millimetre, the interaction time between the mask and the molecule is roughly a trillion times shorter than a second.
We see that this is compatible with high contrast quantum interference."

A thought experiment of Bohr and Einstein

The bars of the nanogratings look resemble the strings of a miniature harp. One may therefore wonder whether the molecules induce vibrations in these strings when they are deflected to the left or the right during quantum diffraction. If this were the case the grating bars could reveal the molecular path through the grating and quantum interference should be destroyed. The experiment thus realizes a thought experiment that was discussed by Nils Bohr and Albert Einstein already decades ago: They asked whether it is possible to know the path a quantum takes through a double slit while observing its wave nature. The solution to this riddle is again provided by Heisenberg's uncertainty principle: Although the molecules give the grating a little kick in the diffraction process this recoil remains always smaller than the quantum mechanical momentum uncertainty of the grating itself. It therefore remains undetectable. Here it is shown that this applies even to membranes that are only one atom thick. [6]

Fattening up Schrödinger's cat

In the famous thought experiment conceived by Erwin Schrödinger in 1935 to illustrate the apparent paradoxes of quantum theory, a cat would be poisoned or not depending on the state of an atom — the atom's state being governed by quantum rules. Because quantum theory required that these rules allowed superpositions, it seemed that Schrödinger's cat could itself exist in a superposition of 'live' and 'dead' states.

The paradox highlights the question of how and when the rules of the quantum world – in which objects such as atoms can exist in several positions at once – give way to the 'classical' mechanics that governs the macroscopic world of our everyday experience, where things must be one way or the other but not both at the same time. This is called the quantum-to-classical transition.

It is now generally thought that 'quantumness' is lost in a process called decoherence, in which disturbances in the immediate environment make the quantum wavefunction describing many-state superpositions appear to collapse into a well-defined, unique classical state. This decoherence tends to become more pronounced the bigger the object, as the opportunities for interacting with the environment increase.

One manifestation of quantum superposition is the interference that can occur between quantum particles passing through two or more narrow slits. In the classical world the particles pass through with their trajectories unchanged, like footballs rolling through a doorway.

But quantum particles can behave like waves, which interfere with one another as they pass through the slits, either enhancing or cancelling each other out to produce a series of bright and dark bands. This interference of quantum particles, first seen for electrons in 1927, is effectively the result of each particle passing through more than one slit: a quantum superposition.

As the experiment is scaled up in size, at some point quantum behaviour (interference) should give way to classical behaviour (no interference). But how big can the particles be before that happens?

Scaling up

In 1999, a team at the University of Vienna demonstrated interference in a many-slit experiment using beams of 60-atom carbon molecules (C60), which are shaped like hollow spheres2. Now Markus Arndt, one of the researchers involved in that experiment, and his colleagues in Austria, Germany, the United States and Switzerland have shown much the same effect for considerably larger molecules tailor-made for the purpose — up to 6 nanometres (millionths of a millimetre) across and composed of up to 430 atoms. These are bigger than some small protein molecules, such as insulin.

In the team's experiment, the beams of molecules are passed through three sets of slits. The first slit, made from a slice of silicon nitride patterned with a grating consisting of slits 90 nanometres wide, forces the molecular beam into a coherent state, in which the matter waves are all in step. The second, a 'virtual grating' made from laser light formed by mirrors into a standing wave of light and dark, causes the interference pattern. The third grating, also of silicon nitride, acts as a mask to admit parts of the interference pattern to a quadrupole mass spectrometer, which counts the number of molecules that pass through.

The researchers report in Nature Communications today that this number rises and falls periodically as the outgoing beam is scanned from left to right, showing that interference, and therefore superposition, is present.

Although this might not sound like a Schrödinger cat experiment, it probes the same quantum effects. It is essentially like firing the cats themselves at the interference grating, rather than making a single cat's fate contingent on an atomic-scale event.

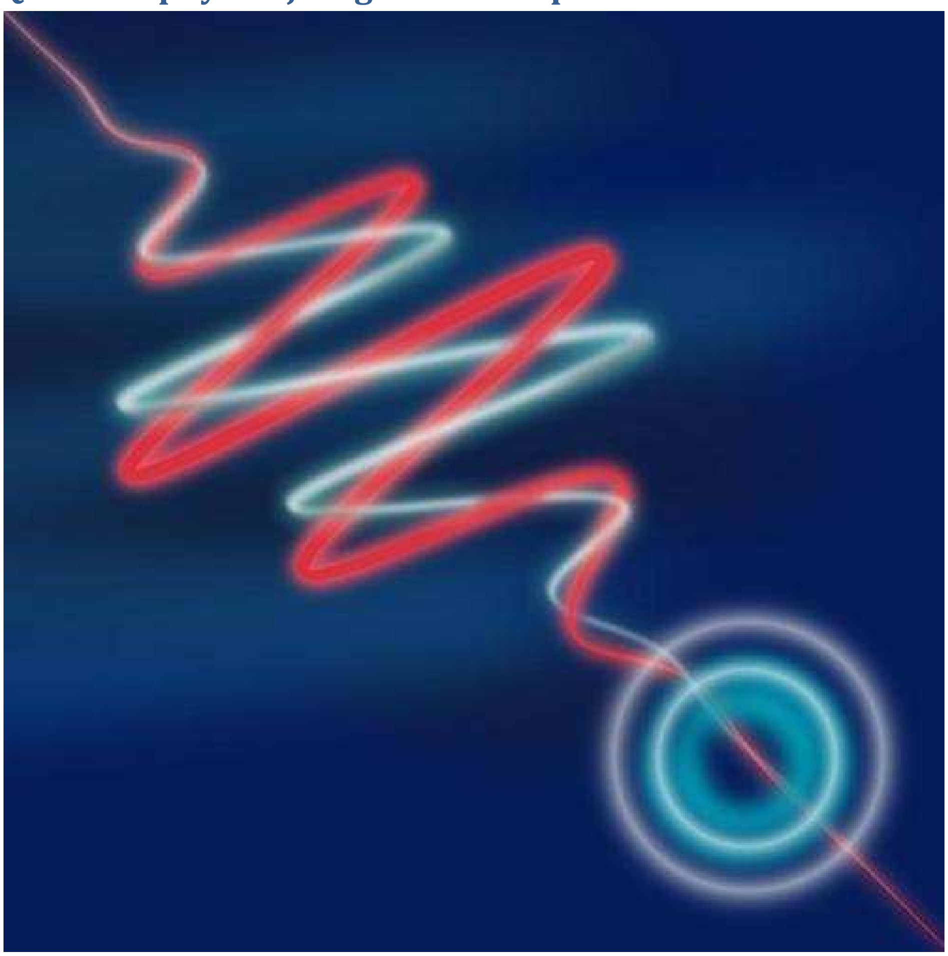
Quantum physicist Martin Plenio of the University of Ulm in Germany calls the study part of an important line of research. "We have perhaps not gained deep new insights into the nature of quantum superposition from this specific experiment," he admits, "but there is hope that with increasing refinement of the experimental technique we will eventually discover something new."

Arndt says that such experiments might eventually allow tests of fundamental aspects of quantum theory, such as how wavefunctions collapse under observation.

"Predictions, such as that gravity might induce wavefunction collapse beyond a certain mass limit, should become testable at significantly higher masses in far-future experiments," he says.

Can living organisms – perhaps not cats, but microorganisms such as bacteria – be placed in superpositions? That has been proposed for viruses3, the smallest of which are just a few nanometres across – although there is no consensus about whether viruses should be considered truly alive. "Tailored molecules are much easier than viruses to handle in such experiments," says Arndt. But he adds that if various technical issues can be addressed, "I don't see why it should not work". [5]

Quantum physics just got less complicated



It's possible to write equations that capture how much can be learned about pairs of properties that are affected by the uncertainty principle. Coles, Kaniewski and Wehner are experts in a form of such equations known as 'entropic uncertainty relations', and they discovered that all the math's previously used to describe wave-particle duality could be reformulated in terms of these relations.

Wave-particle duality is the idea that a quantum object can behave like a wave, but that the wave behaviour disappears if you try to locate the object. It's most simply seen in a double slit experiment, where single particles, electrons, say, are fired one by one at a screen containing two narrow slits. The particles pile up behind the slits not in two heaps as classical objects would, but in a stripy pattern like you'd expect for waves interfering. At least this is what happens until you sneak a look at which slit a particle goes through - do that and the interference pattern vanishes.

The quantum uncertainty principle is the idea that it's impossible to know certain pairs of things about a quantum particle at once. For example, the more precisely you know the position of an atom, the less precisely you can know the speed with which it's moving. It's a limit on the fundamental knowability of nature, not a statement on measurement skill. The new work shows that how much you can learn about the wave versus the particle behavior of a system is constrained in exactly the same way.

Wave-particle duality and uncertainty have been fundamental concepts in quantum physics since the early 1900s. "We were guided by a gut feeling, and only a gut feeling, that there should be a connection," says Coles, who is now a Postdoctoral Fellow at the Institute for Quantum Computing in Waterloo, Canada.

It's possible to write equations that capture how much can be learned about pairs of properties that are affected by the uncertainty principle. Coles, Kaniewski and Wehner are experts in a form of such equations known as 'entropic uncertainty relations', and they discovered that all the math's previously used to describe wave-particle duality could be reformulated in terms of these relations.

"It was like we had discovered the 'Rosetta Stone' that connected two different languages," says Coles. "The literature on wave-particle duality was like hieroglyphics that we could now translate into our native tongue. We had several eureka moments when we finally understood what people had done," he says.

Because the entropic uncertainty relations used in their translation have also been used in proving the security of quantum cryptography - schemes for secure communication using quantum particles - the researchers suggest the work could help inspire new cryptography protocols.

In earlier papers, Wehner and collaborators found connections between the uncertainty principle and other physics, namely quantum 'non-locality' and the second law of thermodynamics. The tantalizing next goal for the researchers is to think about how these pieces fit together and what bigger picture that paints of how nature is constructed. [4]

The Bridge

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

Accelerating charges

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

Relativistic effect

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

Heisenberg Uncertainty Relation

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

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

Wave – Particle Duality

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

Atomic model

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

The Relativistic Bridge

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

The weak interaction

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

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

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

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

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

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

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

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

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

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

The General Weak Interaction

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

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

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

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

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

Fermions and Bosons

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

Van Der Waals force

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

Electromagnetic inertia and mass

Electromagnetic Induction

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

Relativistic change of mass

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

The frequency dependence of mass

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

Electron – Proton mass rate

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

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

Gravity from the point of view of quantum physics

The Gravitational force

The gravitational attractive force is basically a magnetic force.

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

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

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

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

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

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

The Higgs boson

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

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

Higgs mechanism and Quantum Gravity

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

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

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

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

What is the Spin?

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

The Graviton

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

Conclusions

In previous quantum experiments of the same EU collaboration, the thickness of diffraction masks was already as thin as a hundredth of the diameter of a hair.
However, even such structures were still too thick for the diffraction of molecules composed of dozens of atoms. The same force that allows geckos to climb walls restricts the applicability of material gratings in quantum diffraction experiments: Molecules are attracted to the grating bars like the geckos' toes to the wall.
However, once they stick to the surface they are lost to the experiment. A grand challenge was to reduce the material thickness and thus the attractive interactions of these masks down to the ultimate limit while retaining a mechanically stable structure. [6]
Quantum physicist Martin Plenio of the University of Ulm in Germany calls the study part of an important line of research. "We have perhaps not gained deep new insights into the nature of quantum superposition from this specific experiment," he admits, "but there is hope that with increasing refinement of the experimental technique we will eventually discover something new." [5]
In earlier papers, Wehner and collaborators found connections between the uncertainty principle and other physics, namely quantum 'non-locality' and the second law of thermodynamics. The tantalizing next goal for the researchers is to think about how these pieces fit together and what bigger picture that paints of how nature is constructed. [4]
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. Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

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.

References

[1] The Magnetic field of the Electric current and the Magnetic induction

http://academia.edu/3833335/The_Magnetic_field_of_the_Electric_current

[2] 3 Dimensional String Theory

http://academia.edu/3834454/3_Dimensional_String_Theory

[3] Graviton Production By Two Photon and Electron-Photon Processes In Kaluza-Klein Theories With Large Extra Dimensions

http://arxiv.org/abs/hep-ph/9909392

[4] Quantum physics just got less complicated

http://phys.org/news/2014-12-quantum-physics-complicated.html

[5] Fattening up Schrödinger's cat

http://www.nature.com/news/2011/050411/full/news.2011.210.html

[6] Quantum diffraction at a breath of nothing

http://www.sciencedaily.com/releases/2015/08/150825103246.htm

[7] Shaking bosons into fermions

http://phys.org/news/2015-12-bosons-fermions.html

[8] Bose-Einstein condensates miscibility properties reveal surprises

http://phys.org/news/2016-06-bose-einstein-condensates-miscibility-properties-reveal.html

[9] Producing turbulence in a Bose-Einstein condensate yields cascade of wave-like excitations

http://phys.org/news/2016-11-turbulence-bose-einstein-condensate-yields-cascade.html

[10] Looking for entangled atoms in a Bose-Einstein condensate

https://phys.org/news/2017-02-entangled-atoms-bose-einstein-condensate.html

[11] Physicists address loophole in tests of Bell's inequality using 600-year-old starlight

https://phys.org/news/2017-02-physicists-loophole-bell-inequality-year-old.html