QUANTXCER BI-WEEKLY NEWS LETTER

QUANTUM PHYSICS NEWS LETTER 30-JUN-2024

QuantXCer.com

It is a quantum fractal algorithmic universe

TABLE OF CONTENTS

Landmark Study Is Step Towards Energy-Efficient Quantum Computing In Magnets

Researchers from Lancaster University and Radboud University Nijmegen have generated propagating spin waves at the nanoscale and discovered a novel pathway to modulate and amplify them.

Using a laptop – illustrative photo. Image credit: Christin Hume via Unsplash, free license

Their discovery, published in Nature, could pave the way for the development of dissipation free quantum information technologies. As the spin waves do not involve electric currents these chips will be free from associated losses of energy.

The rapidly growing popularity of artificial intelligence comes with an increasing desire for fast and energy efficient computing devices and calls for novel ways to store and process information. The electric currents in conventional devices suffer from losses of energy and subsequent heating of the environment.

One alternative for the “lossy” electric currents is to store and process information in waves, using the spins of the electrons instead of their charges. These spins can be seen as the elementary units of magnets.

Lead author Dr Rostislav Mikhaylovskiy from Lancaster University said: “Our discovery will be essential for future spin-wave based computing. Spin waves are an appealing information carrier as they don’t involve electric currents and therefore do not suffer from resistive losses.”

It has already been known for many years that spins can be kicked out of their equilibrium orientation. After this perturbation, the spins start to precess (i.e. rotate) around their equilibrium position. In magnets neighbouring spins are extremely strongly coupled, forming a net magnetization. Due to this coupling, the spin precession can propagate in the magnetic material, giving rise to a spin wave.

“Observing nonlinear conversion of coherent propagating magnons at nanoscale, which is a prerequisite for any practical magnon-based data processing, has been sought for by many groups worldwide for more than a decade. Therefore, our experiment is a landmark for spin wave studies, which holds the potential to open an entire new research direction on ultrafast coherent magnonics with an eye on the development of dissipation free quantum information technologies.”

The researchers have used the fact that the highest possible frequencies of the spin rotations can be found in materials, in which adjacent spins are canted with respect to each other. To excite such fast spin dynamics, they used a very short pulse of light, the duration of which is shorter than the period of the spin wave, i.e. less than a trillionth of a second. The trick for generating the ultrafast spin wave at the nanoscale is in the photon energy of the light pulse. The material of study exhibits extremely strong absorption at ultraviolet (UV) photon energies, which localises the excitation in a very thin region of only a few tens of nanometres from the interface, which allows spin waves with terahertz (a trillion of Hertz) frequencies and sub-micrometre wavelengths to emerge.

The dynamics of such spin waves is intrinsically nonlinear, meaning that the waves with different frequencies and wavelengths can be converted into each other.

The researchers have now for the first time realized this possibility in practice. They achieved this by exciting the system not with only one, but with two intense laser pulses, separated by a short time delay.

First author Ruben Leenders, former PhD student at Lancaster University, said: “In a typical single pulse excitation experiment, we would simply expect the two spin waves to interfere with each other as any waves do. However, by varying the time delay between the two pulses we found that this superposition of the two waves does not hold.”

The team explained the observations by considering the coupling of the already excited spin wave with the second light pulse. The result of this coupling is that when the spins are already rotating, the second light pulse gives an additional kick to the spins. The strength and the direction of this kick depends on the state of the deflection of the spins at the time that this second light pulse arrives. This mechanism allows for control over the properties of the spin waves such as their amplitude and phase, simply by choosing the appropriate time delay between the excitations.

Physicists Find ‘Spooky Action At A Distance’ At CERN

The researchers have confirmed that quantum entanglement persists between top quarks, the heaviest known fundamental particles.

EXPERIMENTING WITH ENTANGLEMENT: The inside of the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider. Rochester physicists working at the detector have observed spin entanglement between top quarks and top antiquarks persisting at long distances and high speeds. (CERN photo / Maximilien Brice)

An experiment by a group of physicists led by University of Rochester physics professor Regina Demina has produced a significant result related to quantum entanglement—an effect that Albert Einstein called “spooky action at a distance.”

Entanglement concerns the coordinated behavior of miniscule particles that have interacted but then moved apart. Measuring properties—like position or momentum or spin—of one of the separated pair of particles instantaneously changes the results of the other particle, no matter how far the second particle has drifted from its twin. In effect, the state of one entangled particle, or qubit, is inseparable from the other.

Quantum entanglement between stable particles, such as photons or electrons, has been observed.

But Demina and her group broke new ground in that they found, for the first time, entanglement to persist between unstable top quarks and their antimatter partners at distances farther than what can be covered by information transferred at the speed of light. Specifically, the researchers observed spin correlation between the particles.

Hence, the particles demonstrated what Einstein described as "spooky action at a distance."

A 'new avenue' for quantum exploration

The Compact Muon Solenoid (CMS) Collaboration at the European Center for Nuclear Research, or CERN, where the experiment was conducted, reported the finding.

"Confirming the quantum entanglement between the heaviest fundamental particles, the top quarks, has opened up a new avenue to explore the quantum nature of our world at energies far beyond what is accessible," the report read.

CERN, located near Geneva, Switzerland, is the world's largest particle physics laboratory. Production of top quarks requires very high energies accessible at the Large Hadron Collider (LHC), which enables scientists to send high-energy particles spinning around a 17-mile underground track at close to the speed of light.

The phenomenon of entanglement has become the foundation of a burgeoning field of quantum information science, which has broad implications for areas like cryptography and quantum computing.

Top quarks, each as heavy as an atom of gold, can only be produced at colliders, such as LHC, and thus are unlikely to be used to build a quantum computer. But studies like those conducted by Demina and her group can show how long entanglement persists, whether it is passed on to the particles' "daughters" or decay products, and what, if anything, ultimately breaks the entanglement.

Theorists believe that the universe was in an entangled state after its initial fast expansion stage. The new result observed by Demina and her researchers could help scientists understand what led to the loss of the quantum connection in our world.

Top quarks in quantum long-distance relationships

Demina recorded a video for CMS social media channels to explain her group's result. She used the analogy of an indecisive king of a distant land, whom she called "King Top."

King Top gets word that his country is being invaded, so he sends messengers to tell all the people of his land to prepare to defend. But then, Demina explains in the video, he changes his mind and sends messengers to order the people to stand down.

“He keeps flip-flopping like this, and nobody knows what his decision will be at the next moment,” Demina says.

Nobody, Demina goes on to explain, except the leader of one village in this kingdom who is known as “Anti-Top.”

“They know each other’s state of mind at any moment in time,” Demina says.

Demina’s research group consists of herself and graduate student Alan Herrera and postdoctoral fellow Otto Hindrichs.

As a graduate student, Demina was on the team that discovered the top quark in 1995. Later, as a faculty member at Rochester, Demina co-led a team of scientists from across the US that built a tracking device that played a key role in the 2012 discovery of the Higgs boson—an elementary particle that helps explains the origin of mass in the universe. Rochester researchers have a long history at CERN as part of the CMS Collaboration, which brings together physicists from around the globe. Recently, another Rochester team achieved a significant milestone in measuring the electroweak mixing angle, a crucial component of the Standard Model of Particle Physics, which explains how the building blocks of matter interact.

An Alternative Way To Manipulate Quantum States

Researchers at ETH Zurich have shown that quantum states of single electron spins can be controlled by currents of electrons whose spins are evenly aligned. This method could be used in electronic circuit elements in the future.

PhD student Stepan Kovarik in front of the vacuum chamber in which the samples for the experiment are produced. Image credit: D-MATL / Kilian Dietrich, Maria Feofilova and Hasan Baysal

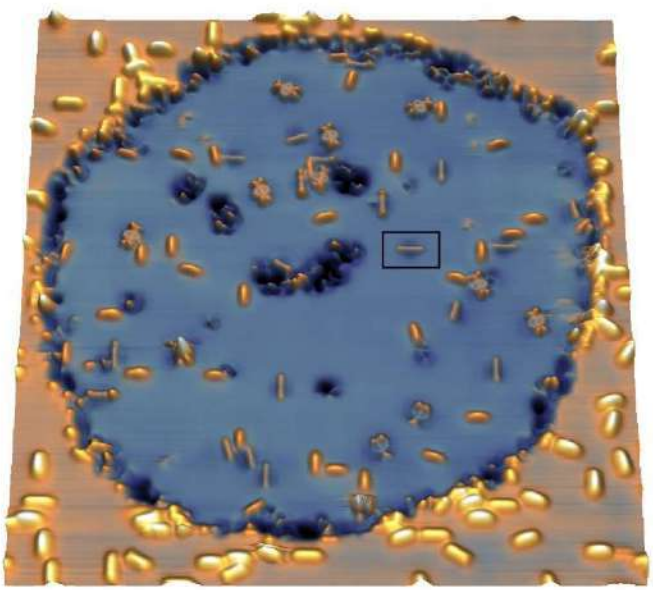
Electrons have an intrinsic angular momentum, the so-called spin, which means that they can align themselves along a magnetic field, much like a compass needle. In addition to the electric charge of electrons, which determines their behaviour in electronic circuits, their spin is increasingly used for storing and processing data. Already now, one can buy MRAM memory elements (magnetic random access memories), in which information is stored in very small but still classical magnets – that is, containing very many electron spins. The MRAM's are based on currents of electrons with spins aligned in parallel that can change the magnetisation at a particular point in a material.

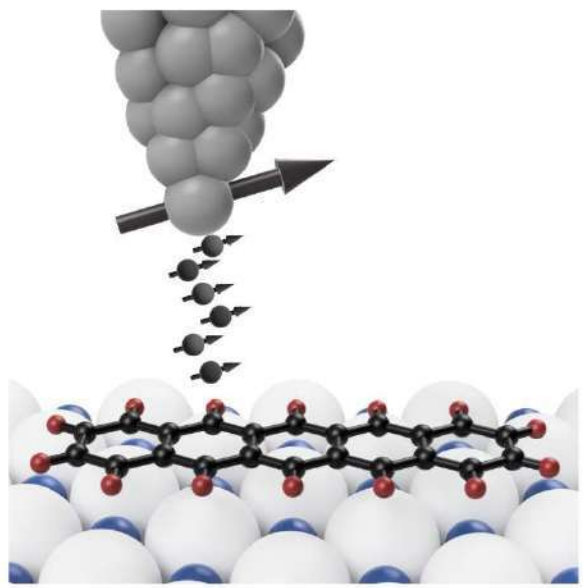
Pietro Gambardella and his collaborators at ETH Zurich now show that such spin-polarized currents can also be used to control the quantum states of single electron spins. Their results, which have just been published in the scientific journal Science, could be used in different technologies in the future, for instance in the control of quantum states of quantum bits (qubits).

Tunnel currents in single molecules

“Traditionally, electron spins are manipulated using electromagnetic fields such as radio-frequency waves or microwaves”, says Sebastian Stepanow, a Senior Scientist in Gambardella’s laboratory. This technique, also known as electron paramagnetic resonance, was developed already in the mid-1940’s and has since been used in different fields such as materials research, chemistry and biophysics. “A few years ago, it was demonstrated that one can induce electron paramagnetic resonance in single atoms; however, so far the exact mechanism for this has been unclear”, says Stepanow.

To study the quantum mechanical processes behind this mechanism more closely, the researchers prepared molecules of pentacene (an aromatic hydrocarbon) on a silver substrate. A thin insulating layer of magnesium oxide had previously been deposited on the substrate. This layer ensures that the electrons in the molecule behave more or less as they would in free space.





Left: Single pentacene molecules (yellow) on the insulating layer (blue). Right: Electrons with spins aligned in parallel (small arrows) tunnel from the tungsten tip (top) to the molecule (bottom). Image credit: ETH Zürich / Aishwarya Vishwakarma und Stepan Kovarik

Using a scanning tunnelling microscope, the researchers first characterised the electron clouds in the molecule. This implies measuring the current that is created when the electrons tunnel quantum mechanically from the tip of a tungsten needle to the molecule. According to the laws of classical physics, the electrons should not be able to hop across the gap between the tip of the needle and the molecule because they lack the necessary energy. Quantum mechanics, however, allows the electrons to “tunnel” through the gap in spite of that lack, which leads to a measurable current.

Miniature magnet on the tip of a needle

This tunnel current can be spin-polarised by first using the tungsten tip to pick up a few iron atoms, which are also on the insulating layer. On the tip, the iron atoms create a kind of miniature magnet. When a tunnel current flows through this magnet, the spins of the electrons in the current all align parallel to its magnetisation.

Now, the researchers applied a constant voltage as well as a fast-oscillating voltage to the magnetised tungsten tip, and they measured the resulting tunnel current. By varying the strength of both voltages and the frequency of the oscillating voltage, they were able to observe characteristic resonances in the tunnel current. The exact shape of these resonances allowed them to draw conclusions about the processes that occurred between the tunnelling electrons and those of the molecule.

Direct spin control by polarized currents

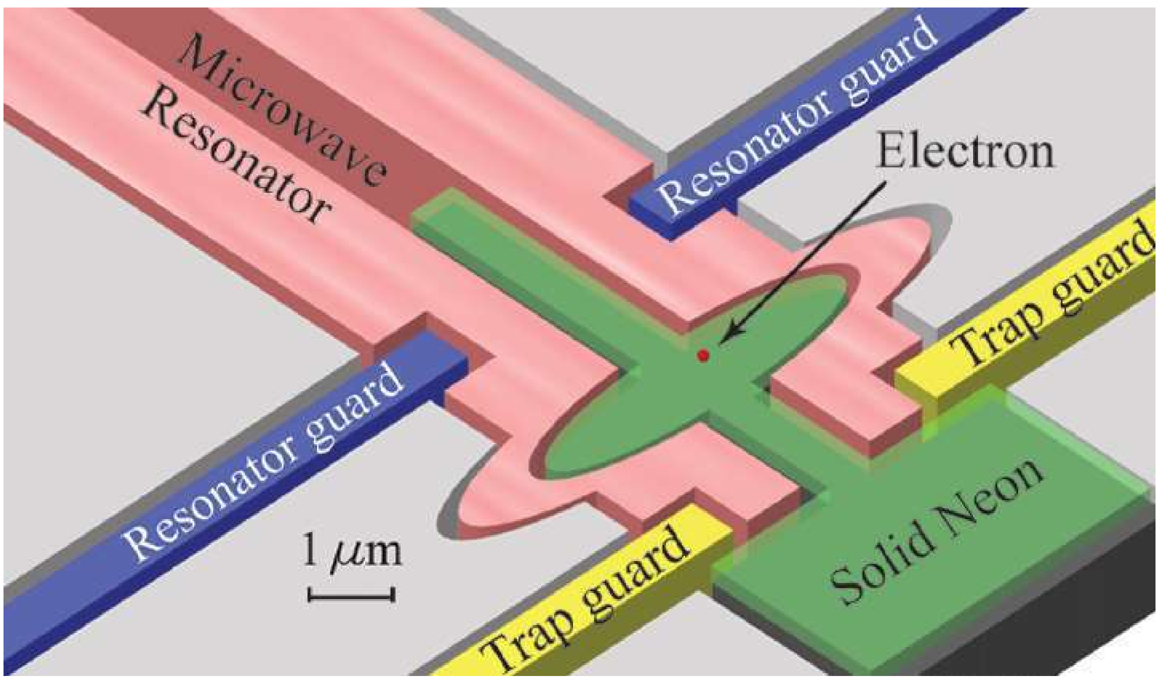
From the data, Stepanow and his colleagues were able to glean two insights. On the one hand, the electron spins in the pentacene molecule reacted to the electromagnetic field created by the alternating voltage in the same way as in ordinary electron paramagnetic resonance. On the other hand, the shape of the resonances suggested that there was an additional process that also influenced the spins of the electrons in the molecule.

“That process is the so-called spin transfer torque, for which the pentacene molecule is an ideal model system”, says PhD student Stepan Kovarik. Spin transfer torque is an effect in which the spin of the molecule is changed under the influence of a spin-polarised current without the direct action of an electromagnetic field. The ETH researchers demonstrated that it is also possible to create quantum mechanical superposition states of the molecular spin in this way. Such superposition states are used, for instance, in quantum technologies.

“This spin control by spin-polarised currents at the quantum level opens up various possible applications”, says Kovarik. In contrast to electromagnetic fields, spin-polarised currents act very locally and can be steered with a precision of less than a nanometre. Such currents could be used to address electronic circuit elements in quantum devices very precisely and thus, for instance, control the quantum states of magnetic qubits.

Understanding Quantum States: Importance Of Precise Topography In Solid Neon Qubits

Quantum computers have the potential to be revolutionary tools because they can perform calculations that would take classical computers many years to resolve.



A diagram of an electron-on-solid-neon quantum bit. Image credit: Wei Guo / FSU

But to make an effective quantum computer, you need a reliable quantum bit, or qubit, that can exist in a simultaneous 0 or 1 state for a sufficiently long period, known as its coherence time.

One promising approach is trapping a single electron on a solid neon surface, called an electron-on-solid-neon qubit. A study led by FAMU-FSU College of Engineering Professor Wei Guo that was published in Physical Review Letters shows new insight into the quantum state that describes the condition of electrons on such a qubit, information that can help engineers build this innovative technology.

Guo’s team found that small bumps on the surface of solid neon in the qubit can naturally bind electrons, which creates ring-shaped quantum states of these electrons. The quantum state refers to the various properties of an electron, such as position, momentum and other characteristics, before they are measured. When the bumps are a certain size, the electron’s transition energy — the amount of energy required for an electron to move from one quantum ring state to another — aligns with the energy of microwave photons, another elementary particle.

This alignment allows for controlled manipulation of the electron, which is needed for quantum computing.

“This work significantly advances our understanding of the electron-trapping mechanism on a promising quantum computing platform,” Guo said. “It not only clarifies puzzling experimental observations but also delivers crucial insights for the design, optimization and control of electron-on-solid-neon qubits.”

Previous work by Guo and collaborators demonstrated the viability of a solid-state single-electron qubit platform using electrons trapped on solid neon. Recent research showed coherence times as great as 0.1 millisecond, or 100 times longer than typical coherence times of 1 microsecond for conventional semiconductor-based and superconductor-based charge qubits.
Coherence time determines how long a quantum system can maintain a superposition state — the ability of the system to be in multiple states at the same time until it is measured, which is one characteristic that gives quantum computers their unique abilities.

The extended coherence time of the electron-on-solid-neon qubit can be attributed to the inertness and purity of solid neon. This qubit system also addresses the issue of liquid surface vibrations, a problem inherent in the more extensively studied electron-on-liquid-helium qubit. The current research offers crucial insights into optimizing the electron-on-solid-neon qubit further.

A crucial part of that optimization is creating qubits that are smooth through most of the solid neon surface but have bumps of the right size where they are needed. Designers want minimal naturally occurring bumps on the surface that attract disruptive background electrical charge. At the same time, intentionally fabricating bumps of the correct size within the microwave resonator on the qubit improves the ability to trap electrons.

“This research underscores the critical need for further study of how different conditions affect neon qubit manufacturing,” Guo said. “Neon injection temperatures and pressure influence the final qubit product. The more control we have over this process, the more precise we can build, and the closer we move to quantum computing that can solve currently unmanageable calculations.”

Researchers Discover New Flat Electronic Bands, Paving Way For Advanced Quantum Materials

In a study published in Nature Communications, a team of scientists led by Rice University’s Qimiao Si predicts the existence of flat electronic bands at the Fermi level. This finding could enable new forms of quantum computing and electronic devices.

A team of scientists led by Qimiao Si predicts the existence of flat electronic bands at the Fermi level. Photo by Jeff Fitlow/Rice University.

Quantum materials are governed by the rules of quantum mechanics, where electrons occupy unique energy states. These states form a ladder, with Fermi energy at the highest rung.

Electrons, being charged, repel each other and move in correlated ways. Si's team found that electron interactions can create new flat bands at the Fermi level, enhancing their importance.

"Most flat bands are located far from the Fermi energy, which limits their impact on the material's properties," said Si, the Harry C. and Olga K. Wiess Professor of Physics and Astronomy at Rice.

Typically, a particle's energy changes with its momentum. But in quantum mechanics, electrons can exhibit quantum interference, where their energy remains flat even when their momentum changes. These are known as flat bands.

"Flat electronic bands can enhance electron interactions, potentially creating new quantum phases and unusual low-energy behaviors," Si said.

These bands are especially sought after in transition metal ions called d-electron materials with specific crystal lattices, where they often show unique properties, Si said.

The team's findings suggest new ways to design these, which could inspire new applications for these materials in quantum bits, qubits and spintronics. Their research shows that electron interactions can link immobile and mobile electron states.

Using a theoretical model, the researchers demonstrated that these interactions can create a new type of Kondo effect, where immobile particles gain mobility by interacting with mobile electrons at the Fermi energy. The Kondo effect describes the scattering of conduction electrons in a metal due to magnetic impurities, resulting in a characteristic change in electrical resistivity with temperature.

"Quantum interference can enable the Kondo effect, allowing us to make significant progress," said Lei Chen, a Ph.D. student at Rice.
A key attribute of the flat bands is their topology, Chen said. "The flat bands pinned to the Fermi energy provide a means to realize new quantum states of matter," he said.

The team's research reveals that this includes anyons and Weyl fermions, or massless quasiparticles and fermions that carry an electric charge. The researchers found that anyons are promising agents for qubits, and materials that host Weyl fermions may find applications in spin-based electronics.

The study also highlights the potential for these materials to be very responsive to external signals and capable of advanced quantum control. The results indicate that the flat bands could lead to strongly correlated topological semimetals at relatively low temperatures potentially operating at high temperatures or even room temperature.

“Our work provides the theoretical foundation for utilizing flat bands in strongly interacting settings to design and control novel quantum materials that operate beyond the realm of low temperatures,” Si said.

END OF NEWS LETTER
– QuantXCer.com