Research updates

Entanglement gets its ‘temperature’ taken

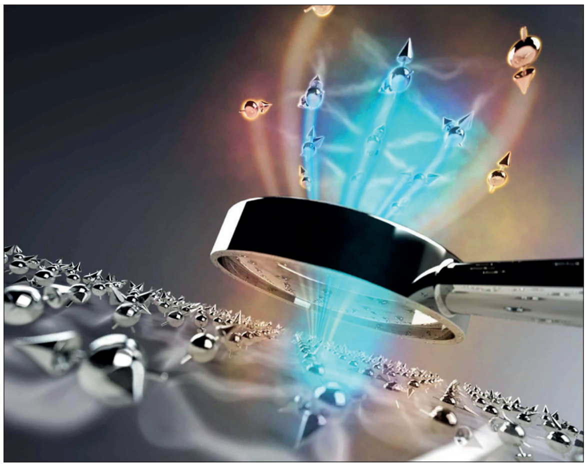
Quantum simulator visualizes large-scale entanglement in materials thanks to a 50-year-old quantum field theorem, as **Martijn Boerkamp** reports

Physicists in Austria have found a quick and efficient way of extracting information on a quantum material’s large-scale entanglement structure thanks to a 50-year-old theorem from quantum field theory. The new method could be applied to areas such as quantum information, quantum chemistry and even high-energy physics (*Nature* **624** 539).

Quantum entanglement is a phenomenon whereby the information contained in an ensemble of particles is encoded in correlations among them. This information cannot be accessed by probing the particles individually, and it is an essential feature of quantum mechanics. As well as being pivotal for quantum computing and quantum communication, entanglement heavily influences the properties of an emerging class of exotic materials. A deeper understanding of it could therefore help scientists understand and solve problems in materials science, condensed-matter physics and beyond.

Learning about the internal entanglement of a large number of entangled particles is notoriously hard, since the complexity of the correlations increases exponentially with the number of particles. This complexity makes it impossible for a classical computer to simulate materials made from such particles. Quantum simulators are better equipped for the task as they can represent the same exponential complexity as the target material they are simulating. However, extracting the entanglement properties of a material with standard techniques still requires an intractably large number of measurements.

Researchers from the University of Innsbruck and the nearby Institute of Quantum Optics and Quantum Information (IQOQI) have now found a more efficient method for evaluating the strength of a system’s entanglement by interpreting it in terms of a local temperature. In the method,



Helene Hainzer

The heat is on Researchers have found a more efficient method for evaluating the strength of a system’s entanglement by interpreting it in terms of a local temperature.

highly entangled regions of the quantum material appear “hot” while weakly entangled regions appear “cold”. Crucially, the exact form of this locally varying temperature field is predicted by quantum field theory, enabling the team to measure temperature profiles more efficiently than was previously possible.

To simulate an entangled quantum material, the Innsbruck-IQOQI team used a system of 51 $^{40}Ca^+$ ions held inside a vacuum chamber by the oscillating electric field of a device called a linear Paul trap. In this set-up each ion can be individually controlled and its quantum state measured with high accuracy. The researchers can then quickly determine the right temperature profiles by placing a feedback loop between the system and a (classical) computer that is constantly generating new profiles and is comparing them with the actual measurements in the experiment. The team could then make measurements to extract properties such as the system’s energy. Finally, they investigated the internal structure of the system’s states by studying the “temperature” profiles, which enabled them to determine the entanglement.

The temperature profiles generated by the researchers show the regions that are strongly correlated with surrounding particles can be considered “hot” (highly entangled) and those that interact very little can be considered “cold” (weakly entangled). The team also confirmed, for the first time, predictions of quantum field theory as adapted to ground states (or low temperature states) of materials via the Bisognano-Wichmann theorem, which was first put forward in 1975 as a way of relating certain Lorentz transformations in space–time to transformations in charge, parity and time. In addition, the method enabled them to visualize the crossover from weakly entangled ground states to strongly entangled excited states of the quantum material.

Team leader Peter Zoller, who holds positions at both Innsbruck and the IQOQI, says that the results and the techniques – quantum protocols running on a quantum simulator – are generally applicable to the simulation of quantum materials. For this reason, he believes they hold broad importance for quantum information science and technology as well as quantum simulation. “For future experiments we [would] like to do this with other platforms and more complicated/interesting model systems,” he told *Physics World*. “Our tools and techniques are very general.”

Marcello Dalmonte, a physicist at the Abdus Salam International Centre for Theoretical Physics in Italy, who was not involved in the research, calls the result “a true ground-breaker”. In his view, the method brings our experimentally testable understanding of entanglement to a new level by unveiling its full complexity. He also thinks the technique will improve our understanding of the relationship between entanglement and physical phenomena, and is excited by the possibility of using it to solve key questions in theoretical physics, such as reaching a better understanding of the operator entanglement structure for mixed states.

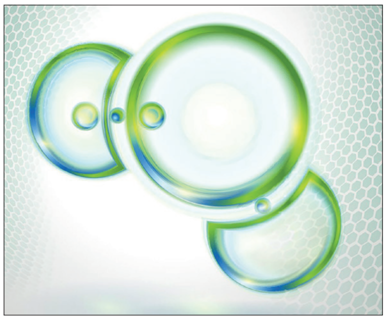
Optics

Light found to evaporate water without heat

Researchers in the US have found that under certain conditions light can cause water to evaporate directly, without heating it first. The process works by cleaving water clusters from the water–air interface, with researchers at the Massachusetts Institute of Technology (MIT) dubbing it the "photomolecular effect" in analogy with the well-known photoelectric effect (*Proc. Natl. Acad. Sci.* **120** e2312751120).

Conventional wisdom states that evaporation requires heat, but scientists have been studying an alternative, which relies on the interaction between sunlight and material surfaces. As water does not, on its own, absorb much visible light, previous studies involved dispersing a black, porous, light-absorbing material in a container of water to aid the conversion of sunlight into heat.

However, in 2018 a team of researchers led by Guihua Yu at the University of Texas at Austin, US, repeated this experiment with a black hydrogel (a material that holds water). They found that the material's thermal evaporation rate was twice as fast as it should have been, given the total amount of heat energy the sample received and assuming the established mechanism was the only one at work.



Shutterstock/Valenty

Illuminating result The newly dubbed "photomolecular effect" could have applications in desalination and waste-water treatment.

MIT nanotechnologist and mechanical engineer Gang Chen and colleagues were not convinced by the team's suggested explanation: that water in the black hydrogel might have a much lower latent heat than ordinary water. "I realized that the only thing in common between all these experiments was the increased surface area between the water and air interface," Chen says. "I therefore asked myself if a surface effect was responsible and this is where the photoelectric analogy came in."

Chen wondered if the team's observations might involve a quadrupole force acting on a permanent dipole at the air–water interface. Although Chen's theory was still at the "hand-waving" stage, it guided new MIT experiments. Success came when they were able to show that while neither pure water nor the hydrogels they studied absorb visible light, partially wetted hydrogels do. "With the idea that visible light can cleave off water molecular clusters, we were also able to explain the 2018 experiments," says Chen.

In these photomolecular processes, a photon cleaves off a water molecular cluster from the water–air interface. Compared to thermal evaporation, which evaporates water molecules one-by-one, and therefore needs energy to break the bonds between water molecules, photomolecular evaporation is more efficient at evaporating than heat alone. Chen believes this new mechanism could be at play in the Earth's water cycle, global warming and plant growth. The discovery could also be used in desalination and waste-water treatment.

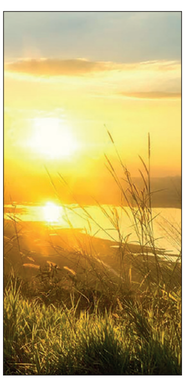
Isabelle Dumé

Materials

Solar-powered fabric cools in the day and warms at night

Researchers in China have unveiled a new concept for solar-powered clothing that can regulate its wearer's body temperature. Created by Ziyuan Wang and colleagues at Nankai University, the design combines electrocaloric devices with state-of-the-art flexible solar cells (*Science* 382 1291).

Thermoregulating clothing aims to keep the body at a safe and comfortable temperature in a wide range of environments. Broadly, it falls into two categories: passive and active. Passive thermoregulation uses materials that exploit effects including absorption, radiation and the latent heat of phase transitions to keep their wearers comfortable. A key advantage of a passive approach is that an external power source is not needed. However, passive thermoregulation normally goes in one direction with garments either having a cooling or warming effect – but not both.



Shutterstock/PK-Studio

Solar fashion A new fabric can switch from cooling to heating mode as sunlight fades.

So-called "bidirectional thermoregulation" is usually achieved using active materials that employ mechanisms such as coolant circulation and fluidic channels to achieve rapid heating and cooling. These systems are usually powered by batteries, which add weight and must be recharged. In principle, however, they could also be powered by harvesting energy from the Sun – but this has proven to be a significant design challenge. To tackle this, Wang and colleagues built a small piece of wearable material by integrating a flexible solar cell onto a flexible electrocaloric module. The latter is a device that reversibly changes temperature in response to applied electric fields.

When placed in sunlight, the solar cell harvested more than enough energy for the electrocaloric module to cool a wearer's skin by 10 °C in hot weather, with any excess energy being stored in a small separate battery. In darkness, the device can be switched to warming mode and the stored energy used to warm the wearer's skin by as much as 3 °C. Altogether, the device can achieve thermoregulation throughout a 24-hour period.

By integrating this technology into wearable fabrics, Wang's team hopes the innovation could lead to a new generation of practical, solar-powered clothing that helps wearers adapt to complex and challenging environments such as scorching deserts, frigid polar regions, and climates with rapid swings in temperature. It could even be adapted for use in space, where temperatures shoot up in direct sunlight, but plummet in shade.

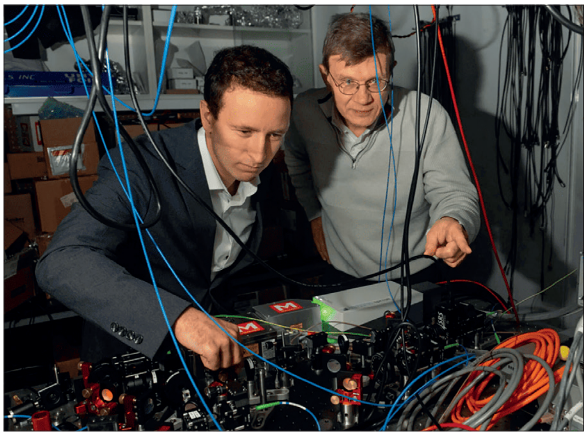
Sam Jarman

Quantum physics

Quantum processor integrates 48 logical qubits

A quantum processor with 48 logical qubits that can execute algorithms while correcting errors in real time has been unveiled in the US. Created by Mikhail Lukin and colleagues at Harvard University, the Massachusetts Institute of Technology and QuEra, the work could lead to the development of quantum computers with large numbers of logical qubits. (*Nature* doi:/10.1038/s41586-023-06927-3).

Quantum processors are very susceptible to disruption from environmental noise, which destroys the delicate quantum states that are used to store and process information. Quantum error correction addresses the noise problem by having a group of qubits work together as one qubit, which is called a logical qubit. The idea is that the information held by a logical qubit is spread out over a number of physical qubits, which work together to identify and correct errors as they occur. Researchers hope to use logical qubits to replace individual qubits in quantum computing architectures, making them resilient against errors when running algorithms.



Jon Chase/Harvard University

Numbers game
Work by Dolev Bluvstein (left) and Mikhail Lukin could lead to quantum computers that offer large numbers of logical qubits.

Recently experiments reached the milestone of using two logical qubits to operate a single quantum logic gate – and in their new study, Lukin and colleagues explored how a much larger system could be created using neutral atom arrays. These are grids of ultracold rubidium atoms trapped by optical tweezers. These atoms can be put into highly excited Rydberg states, which enables the atoms to act as qubits that can exchange quantum information. Neutral atom arrays are especially well suited for logical qubit architectures as they can be dynamically reconfigured during a computation, while preserving their quantum information.

Taking advantage of these properties, Lukin and colleagues created a programmable quantum processor that is based on the control of logical qubits in neutral atom arrays, and used their platform to run a series of programmable logical algorithms. This approach allowed the team to vastly improve on the results of recent experiments: encoding up to 48 logical qubits, containing up to 228 two-qubit logic gates.

With its in-built error correction, the processor dramatically improved the performance of the algorithms. This allowed the team to explore several important features of logical operations in quantum computers, including the application of large-scale error correction across large numbers of qubits, and tolerance against noise and imperfections in quantum hardware. The scientists are optimistic that their research could soon pave the way for large-scale logical quantum processors.

Sam Jarman

Biophysics

Viruses change structure at human body temperatures to infect us better

The structure of viral DNA has been uncovered in unprecedented detail, shedding new light on changes that make the macromolecule more fluid-like at temperatures close to that of the human body. According to the researchers, these structural changes help explain the speed with which viruses release DNA into host cells, so facilitating infection (*Proc. Natl. Acad. Sci.* **120** e2220518120).

Unlike bacteria or fungi, viruses cannot survive without a host. After infecting a cell, they produce new virus particles that then infect other cells. To protect the virus's genetic information in the interim, the viral DNA is usually enclosed within a protein shell known as a capsid. In the latest work, Alex Evilevitch from Lund University, Sweden, and colleagues used small-angle neutron scattering to image the structure of the virus DNA and its density inside the capsid at different temperatures.

The researchers previously found that DNA inside the capsid suddenly changes structure at 37 °C – the normal temperature of the human body. This implies that structure plays a central role the way the virus delivers its genetic material into a cell – the first step in an infection. Notably, the DNA within viruses is packaged at a very high density, and is hundreds of times longer than the diameter of the capsid. Even so, during infection, the DNA is rapidly ejected from the capsid through a single pore.

How this happens is a puzzle and so Evilevitch and colleagues investigated how temperature affects the structure of the viral genome, since it is known that at optimum body temperature (37 °C) viruses can quickly eject their fluid-like DNA. They found, for the first time, that DNA inside a virus capsid coexists in two phases – a hexagonally ordered high-density phase in the periphery of the capsid and a low-density less-ordered, fluid-like phase in the core. "Increases in temperature trigger a transition in DNA where a portion of the ordered DNA in the periphery moves to the less ordered phase in the centre, which allows the DNA ejection from the virus into a cell to begin," Evilevitch says.

Alex Evilevitch and Ting Liu

Viral load
Researchers have used small-angle neutron scattering to investigate the structure of viral DNA.

According to Evilevitch, the findings show that temperature plays a significant role in the infection process and also that neutron scattering is a useful tool for studying the structure of viral genomes inside viral capsids.

Isabelle Dumé

Qubits made with entangled molecules

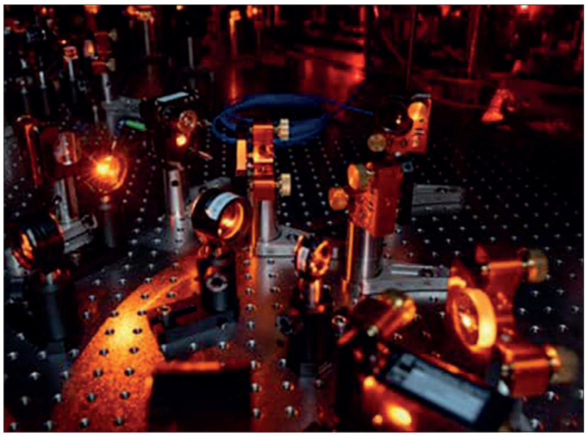
Two independent groups report using ultracold molecules to encode quantum bits, as **Martijn Boerkamp** explains

Ultracold molecules are a step closer to becoming a viable platform for quantum technology thanks to two independent teams who have shown it is possible to entangle pairs of molecules and programme them as quantum bits (qubits). As molecules offer new ways to encode quantum information and can interact with each other over long distances, the work offers new possibilities in quantum computing and quantum simulations beyond those provided by other types of qubits (*Science* **382** 1138 and **382** 1143).

The advent of fast and highly capable quantum devices is widely predicted to revolutionize computing. That said, current qubit platforms such as trapped ions, quantum dots, Rydberg atoms and specially-designed superconducting circuits are restricted to "only" 0s, 1s and superpositions. Qubits made of molecules could change that. By definition, molecules consist of at least two atoms, which can vibrate and rotate with respect to each other, thereby creating additional states for storing and processing information.

Making molecular qubits is no easy task, however, because these additional vibrational and rotational states must be tightly controlled. In particular, molecular qubits can only exist at ultracold temperatures, since any heat will cause the molecules to vibrate, rotate and translate so much that they decohere – meaning they lose their quantum nature and their ability to perform computations.

The latest research, led by Lawrence Cheuk of Princeton University, US and independently by John Doyle and Kang-Kuen Ni of Harvard University, Wolfgang Ketterle at the Massachusetts Institute of Technology (MIT) and Eun-mi Chae from Korea University, focuses on molecules of calcium monofluoride (CaF). As fluoride strongly attracts electrons, these molecules are highly polar, which allows the opposite sides of two molecules to attract and interact via a mechanism called dipolar spin exchange. This interaction leaves the molecules entangled, meaning that their quantum states are connected regardless of the distance between them. Information can then be encoded into the rotational states of the entangled molecules (the non-rotating part represents a "0" and the rotating part a "1") to create a two-qubit gate – a building block of quantum computing.



R Soden, Department of Physics, Princeton University

Cool finding
Making qubits from ultracold molecules means that additional states can be created and used to store and process quantum information.

Opposites attract

To implement their two-qubit gates, both groups begin by laser cooling CaF molecules to microkelvin temperatures and using optical tweezers to create arrays of 20–40 individually-trapped molecules. At this point, the Princeton team took an extra step of making its molecular array defect-free by removing empty tweezer sites. Both groups then brought pairs of molecules to within micrometres of each other and let them interact. To avoid decoherence, the two groups selected a particularly favourable set of rotational states to encode their qubits and applied microwave pulses to decouple the molecules from perturbations caused by interactions with their environment.

By precisely controlling the molecules' interaction time, the two groups implemented a two-qubit gate that brings the molecules into so-called Bell states. These states are maximally entangled, and the Princeton and Harvard-MIT teams created them with a fidelity (or quality) of 0.54 and 0.89, respectively. The Princeton researchers further showed that this entanglement was created deterministically (that is, on-demand) and demonstrated the robustness of the Bell states by showing that they remain coherent even if the molecules are moved apart.

The Harvard-MIT collaborators, meanwhile, demonstrated that they could control the rotational states of the molecules. By rotating the molecules 90 degrees, they could alter the molecular interaction from antiferromagnetic to ferromagnetic and vice versa. This level of control makes it possible to probe the intermolecular interactions, which could be useful for simulating condensed-matter systems such as lattice spin models. Crucially, both teams succeeded in creating a maximally entangled two-qubit gate, which, when combined with single qubit rotations, is sufficient for universal quantum computing.

As a next step, Doyle says that his collaboration has already implemented a powerful technique called Raman sideband cooling to cool the molecules further, pushing them towards the motional ground state of the optical tweezer arrays that confine them. These lower temperatures should allow longer coherence times for the dipolar interaction. The collaboration is also planning to entangle more complex molecules like CaOH and SrOH. "We already worked out the necessary milestones before we can entangle these polyatomic molecules, such as laser-cooling and loading them into a magneto-optical trap, as well as creating an optical tweezer array of CaOH molecules," Doyle told *Physics World*.

Cheuk, of Princeton, says the team's to-do list includes improving the coherence times of the molecules, the fidelity of preparing the molecular qubits, and the fidelity of the two-qubit gates. As they have established the key building blocks of preparing and entangling individual molecules, they are also interested in using their molecular arrays as a new platform to simulate larger-scale systems.