Raiders of the lost dimension

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Ancient Chinese warriors are yet again helping scientists from the National High Magnetic Field Laboratory and their collaborators unravel some of the mysteries of the natural world.

It all starts with a pigment called Han purple that was used more than 2,000 years ago to color Xi'an terra cotta warriors of the Qian Dynasty. The pigment is known in the scientific world as $BaCuSi_20_6$ -- and when magnet lab scientists exposed it to very high magnetic fields and very low temperatures, it entered a state of matter that is rarely observed.

The most recent research, published in today's issue of the journal *Nature*, shows that at the lowest temperature point at which the change of state occurs -- called the Quantum Critical Point -- the Han purple pigment actually loses a dimension: it goes from 3D to 2D.

Theoretical physicists have postulated that this kind of dimensional reduction might help explain some mysterious properties of other materials (high temperature superconductors and metallic magnets known as "heavy fermions" for example) near the absolute zero of temperature, but until now, a change in dimension had not been experimentally observed.

We live in three dimensions; up-down, front-back and left-right are the options. A sound wave, for example, "exists" in three dimensions and propagates in all of these directions simultaneously. If we could take a picture it would look like an expanding balloon. A wave in two dimensions looks like ripples on the surface of a pond. Ripples propagate on the surface only; they don't propagate perpendicular to the surface, which is the third dimension.

"As often happens in science, we found something we weren't looking for," said Marcelo Jaime, an experimental physicist at the magnet lab's Pulsed Field Facility in Los Alamos, N.M. "Much to our surprise, we found that when the temperature is low enough, the transition into the new magnetic state occurs in an unexpected way."

The experiment was performed at the magnet lab's DC Field Facility at Florida State University by Neil Harrison from the Pulsed Field Facility and Suchitra Sebastian from Stanford University, in collaboration with a team of scientists from these institutions.

They observed that at high magnetic fields (above 23 tesla) and temperatures between 1 and 3 degrees Kelvin (approximately -460 degrees Fahrenheit), the magnetic waves in three-dimensional crystals of Han purple "exist" in a three-dimensional world as per conventional wisdom. However, below those temperatures, near the quantum limit, one of the dimensions is no longer accessible, with the unexpected consequence that magnetic ripples propagate in only two dimensions. (Kelvin is the temperature scale used by scientists; zero degrees Kelvin is absolute zero, a temperature so low it is experimentally unreachable.)

The magnetic waves in the pigment exist in a unique state of matter called a Bose Einstein condensate (BEC), so named for its theoretical postulation by Satyendra Nath Bose and Albert Einstein. In the BEC state, the individual waves (associated with magnetism from pairs of copper atoms in $BaCuSi_20_6$) lose their identities and condense into one giant wave of undulating magnetism. As the temperature is lowered, this magnetic wave becomes sensitive to vertical arrangement of individual copper layers, which are shifted relative to each other – a phenomenon known as "geometrical frustration." This makes it difficult for the magnetic wave to exist in the third up-down dimension any longer, and leads to a change to a two-dimensional wave, in very much the same way as ripples are confined to the surface of a pond. The theoretical framework that leads to this interpretation was provided by Cristian Batista at LANL.

Other members of the research team include Peter Sharma and Jaime of the National High Magnetic Field Laboratory at LANL, Luis Balicas from the NHMFL at FSU, Ian Fisher of Stanford, and Naoki Kawashima of the University of Tokyo.

"This is truly paramount work," said Alex Lacerda, associate director for user operations for all three sites of the magnet lab and director of the Pulsed Field Facility. "It takes world-class magnets, instruments and people, all of which the mag lab has, to produce these kinds of landmark results."

Research such as this could aid in the understanding of processes important for quantum computers. It is believed that this type of computer would operate based on quantum magnetism to perform many different computations at once. Theorists believe this capability could produce answers to mathematical problems much more quickly than is currently possible with conventional computers.

Scientists also think that someday, information gleaned from BEC will help make instruments for very sensitive measurement and tiny structures that are much smaller than computer chips.

Source: National High Magnetic Field Laboratory