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Using magnetic frustration to probe new quantum possibilities

Research in the lab of UC Santa Barbara materials professor Stephen Wilson is focused on understanding the fundamental physics behind unusual states of matter and developing materials that can host the kinds of properties needed for quantum functionalities.

In a paper published in the journal Nature Materials, Wilson's lab group reports on an innovative way to use a phenomenon referred to as *frustration* of long-range order in a material system to engineer unconventional magnetic states with potential relevance for quantum technologies. At the same time, Wilson emphasized, "This is fundamental science aimed at addressing a basic question. It's meant to probe what physics may be possible for future devices."

The paper, "Interleaved bond frustration in a triangular lattice antiferromagnet," explores how several types of frustration can come into play in this realm. One is geometric frustration, which refers to when the magnetic moments of a material are unable to settle in a single ordered arrangement, leaving them in a fluctuating state, or frustrated.

"You can think of magnetism as being derived from tiny bar magnets sitting at the atomic sites in a crystal lattice," Wilson said. "Those bar magnets are what we call *magnetic dipole moments,* and they can interact and orient themselves relative to one another in specific ways, depending on the details of a material, to minimize their energy or, said another way, to realize their ground state.” That is the lowest energy state for any system, and any system at absolute zero temperature exists in its ground state.

“If those magnetic moments interact in a way that wants them to point antiparallel to one another, we call that antiferromagnetism,” Wilson added. “If they want to interact in this antiferromagnetic way, and if they are sitting on atoms forming a square network, then each moment can be antiparallel to its neighbors. The moments are ‘happy,’ and that is the ground state. In a different network, however, such as a triangle, not every moment can point opposite to its neighbors. They compete with one another, or are ‘frustrated,’ because they don’t know which way to point to realize the ground state of the system. The moments seek equilibrium but are frustrated from achieving it by the geometry of the space they occupy.”

It turns out that a similar type of frustration can occur with other aspects of the electron, its charge, for instance. In particular, if two neighboring ions try to share an electron across a bond, they can form what is called an *atomic dimer*. Similar to the case of antiferromagnetism, the formation of these dimers can be frustrated in certain lattice geometries, such as triangular lattices or honeycomb networks. What can then result is a frustrated bond network that is highly susceptible to strain, which can act to relieve the frustration of the bond network. Wilson’s paper examines an extremely rare system of materials where both of these types of frustration were found to coexist.

Wilson describes this advance as “exciting” because it opens a window into functional control over one frustrated system via a perturbation that impacts the other. Over the past six or seven years, researchers have found that they can engineer a frustrated magnetic state by using materials built from triangular networks of lanthanides, a group of elements located at the bottom of the periodic table.

“In principle, this triangular lattice network of properly chosen lanthanide moments can cause a special kind of intrinsically quantum disordered state to arise,” Wilson said. “One thing we tried to do in this project was to functionalize that exotic state by embedding it in a crystal lattice that has an additional degree of bond frustration."

While there are many different "flavors" of quantum disordered magnetism, in principle, Wilson noted, "Some states can host long-range entanglement of spins, which is of interest in the realm of quantum information. Gaining control over those states via applying a strain in the frustrated bond network would be exciting."

If you have two highly frustrated layers that are both very sensitive to perturbations, like strain, or, in the magnetic case, a magnetic field, then the question is whether you can couple the two together, because when one is biased and decides to order, it can potentially couple to the second one and alter it.

"It's a way of imparting in things a functionality or response to other things to which it would otherwise not respond," Wilson explained. "So, in principle, one can engineer large ferroic responses.You can apply a bit of strain, which induces magnetic order, or you can apply a bit of magnetic field and induce changes to the structure.

"Again, in principle, if you can find a quantum disordered ground state that hosts long-range entanglement, the question then becomes whether you can access that entanglement by, for instance, coupling to another layer, such as bond frustration."

Wilson also wants to discover whether, through this process, it is possible to realize different types of *intertwined order. "*Basically, you could have different types of order that get nucleated because of the proximity of these two frustrated lattices," he said. "That's the big-picture idea."

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