FROM THE LAB

A WEEKLY UPDATE FROM INDIA'S FINEST RESEARCH INSTITUTES

In search of Quantum Spin Liquid

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WE ARE familiar with three common states of matter or phases: solid, liquid, and gas. Transformation between them is possible by tuning interactions between constituent particles by changing, for example, temperature or pressure. Ice becomes water if temperature is increased. Gases can be liquefied when pressurised.

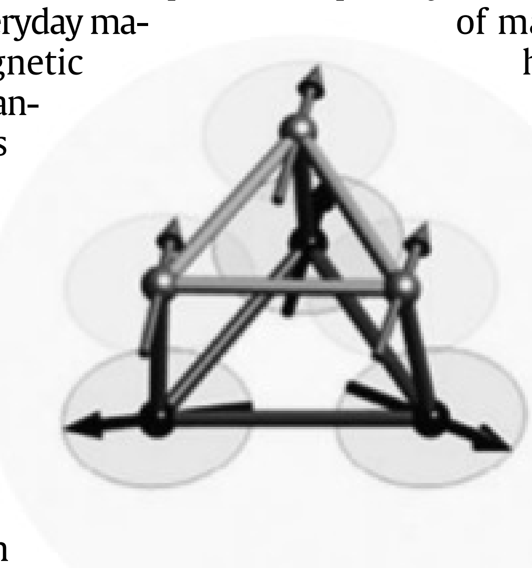
Electrons in solid materials are also said to exist in different phases, depending on the way they are arranged and the way they interact with each other. Magnetic solids, for example, exist in two phases — paramagnetic phase and ferromagnetic phase. In ferromagnetic phase, the spin — an intrinsic property of electrons, it can be up or down relative to an external magnetic field — all the electrons point in the same direction. This can be compared to the solid state of everyday materials. In paramagnetic phase, spins are all randomly aligned. This is analogous to the gaseous phase.

The liquid state, however, is elusive. This is because most matter, when cooled to low temperatures, freezes into a solid. Similarly, in conventional magnets, "electronic spins", which are fluctuating randomly at high temperatures, come to rest and become rigidly oriented as temperature is lowered. When temperature nears absolute zero, thermal fluctuations — randomness caused by temperature — almost cease. But, "quantum fluctuations" become apparent. This refers to the uncertainties that are characteristic to a quantum particle like electron, in this case the uncertainty related to spin direction. In accordance with the Heisenberg's Uncertainty Principle, it becomes impossible to determine the spin direction of the electron. The spin is equally likely to be up or down, left or right.

If the quantum fluctuations are strong, they can lead to "melting" of the 'magnetic' solid just like thermal fluctuations do. This is the liquid state where the electronic spins do not have fixed orientations even at absolute zero temperature. This state is called 'quantum spin liquid', or QSL.

This uncertainty in spin direction can be expected in materials in which electrons are arranged in a triangular formation and their interactions are anti-ferromagnetic, that is, neighbouring electrons are aligned in anti-parallel direction. In such formation, spins on all the three corners cannot be anti-parallel to each other. This leads to a situation called 'geometrical magnetic frustration' that prevents the spins on the three corners from choosing any particular fixed orientation. The resulting state of perpetual fluctuation is the QSL state. Ferromagnetic interactions, in which all spins are aligned parallel to each other, do not frustrate because spins at all the corners can point in the same direction. For these reasons, the search for QSL candidates was restricted to only a few materials with lattices made up of triangular motifs and anti-ferromagnetic interactions.

However, we have now been able to show that QSLs can occur in more complex crystals with far richer combinations of magnetic interactions. We have investigated the structure and thermodynamic properties of calcium chromium oxide ($Ca_{10}Cr_7O_{28}$) that has a complex set of isotropic magnetic interactions, consisting of dominant ferromagnetic interactions and weaker residual anti-ferromagnetic interactions which, according to conventional understanding, would not favor spin liquid behaviour. Several microscopic measurements have, however, shown that the spins in these samples retain their collective motion even at temperatures as low as 20 milli-kelvin, and behave like a QSL.



A section from the crystal lattice of calcium-chromium oxide

QSLs might find uses in building thermal conductors that are also electrical insulators. More importantly, applications of spin liquids in quantum computing have also been discussed where the topological excitations of the QSL can be used as a 'qubit' which are the building blocks of quantum computers.

For your research to be considered for this column, please write to Senior Editor Amitabh Sinha at amitabh.sinha@expressindia.com