

Higgs transition of north and south poles of electrons in a magnet

August 7 2012

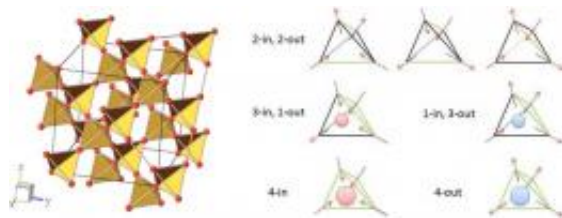


Figure one shows the pyrochlore lattice structure of spin ice and spins on a tetrahedron. The left shows Pyrochlore lattice structure. Each lattice point (red) hosts an electron spin. The right shows Directions and configurations allowed for spins located at vertex points of the unit tetrahedron of the pyrochlore lattice structure. Credit: RIKEN

Minimal evidence of a Higgs transition of north and south poles of electron spins was observed in a magnet $\text{Yb}_2\text{Ti}_2\text{O}_7$ at the absolute temperature 2 0.21 K. A fractionalization of these monopoles from electron spins was observed on cooling to 0.3 K. On further cooling below 0.21 K, the material showed the ferromagnetism to be understood as a superconductivity of monopoles. The work is reported in an online science journal *Nature Communications* on August 7, by an international collaboration team.

Electrons rotate like the earth, acting as tiny magnets called spins in magnetic materials. Usually, these spins form a magnetic order on cooling, and the monopoles, namely, north and south poles of electron

spins, are confined to each other. In magnetic materials called [spin ice](#) ³, the spins remain unordered even at low temperatures, and the monopoles behave as if they are fractionalized while unstable. Since 2010, on the other hand, Dr. Onoda and coworkers have predicted a so-called quantum spin ice ⁴ that can exhibit a magnetic order realized by a Bose-Einstein condensation of monopoles. In this case, a coupling to fictitious [electromagnetic fields](#), called gauge fields, endows a mass for otherwise gapless spin excitations in the ordered state, forming an analogous [superconducting state](#) of monopoles via the Higgs mechanism⁵. Now, cooling a quantum spin ice material $\text{Yb}_2\text{Ti}_2\text{O}_7$ to 0.21 K, the team observed a transition from a state with fractionalized unstable monopoles to a ferromagnetic state with condensed stable monopoles, indicating a Higgs transition of monopoles. This state hosting dissipationless monopole current of spins is expected to play important roles in spintronics that aims at efficient controls of magnets for application.

In most of electrically insulating magnets, electrons form [tiny magnets](#) called spins by their rotation. A macroscopic number of spins usually show an order at low temperatures, demonstrating a spontaneous symmetry breaking. For instance, in ferromagnets and antiferromagnets, spins show parallel and antiparallel alignments, respectively. However, a geometrical frustration, which will be explained below, sometimes suppresses a formation of the magnetic order, as in materials called spin ice, $\text{Dy}_2\text{Ti}_2\text{O}_7$ and $\text{Ho}_2\text{Ti}_2\text{O}_7$.

Spins in spin ice are localized at points of a pyrochlore lattice which has a network of corner-sharing tetrahedra (Fig.1, left). Each spin can point only to the "in" or "out" towards the center of the tetrahedron. Two adjacent spins interact with each other so that they form a pair of "in" and "out". However, it is impossible that all the pairs of adjacent spins on a tetrahedron take such pair of "in" and "out" (Fig.1, right: black lines). Because of this frustration, the four spins on each tetrahedron are compromised to form a "2-in, 2-out" structure, as the most stable one

(Fig.1, upper right). This is called the ice rule. Yet a huge number of spin configurations satisfy the ice rule over the crystal, preventing a spin ordering even at low temperatures. Inverting a single spin in the ice-rule state creates a pair of unstable "3-in, 1-out" and "1-in, 3-out" tetrahedra hosting a north pole and a south pole of spins at the center, respectively (Fig.1, middle right). These north/south poles are recognized as monopoles fractionalized from electron spins, whereas they are unstable and disappear eventually.

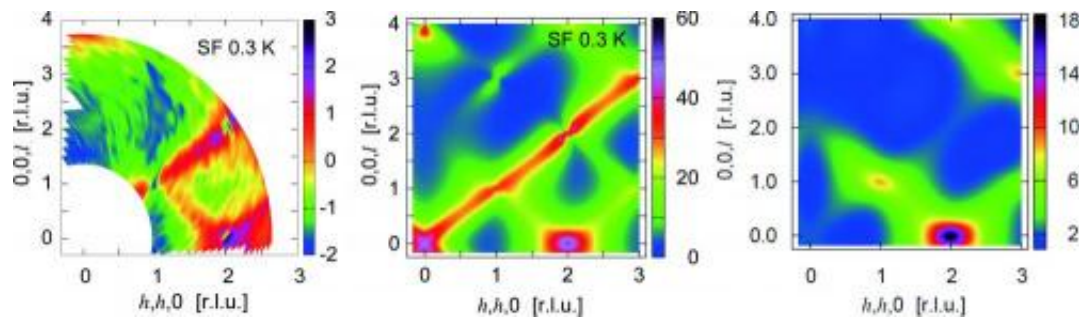


Figure two shows the neutron-scattering intensity map at 0.3 K. The left shows experimental result on Yb₂Ti₂O₇. The middle shows the theoretical results based on the quantum spin ice model. The right shows a map for conventional magnets slightly above a magnetic transition temperature. Credit: RIKEN

In 2010-2012, Dr. Onoda and coworkers derived a theoretical model called "quantum spin ice" for [magnetic materials](#) like Pr₂Zr₂O₇ and Yb₂Ti₂O₇, where monopoles exhibit a motion obeying the quantum mechanics. It has been shown that in certain cases, monopoles undergo a Bose-Einstein condensation leading to a magnetic order where each spin points to a direction largely tilted from the "in" or "out". Now the collaboration team, cooling a quantum spin ice magnet Yb₂Ti₂O₇, challenged an observation of a transition, from the state with fractionalized but unstable monopoles, to the other having condensed

monopoles.

The research team irradiated a neutron beam on the single crystal of $\text{Yb}_2\text{Ti}_2\text{O}_7$ with the neutron spins being aligned, and then analyzed configurations of electron spins from a pattern of the scattering intensity of neutrons by electron spins. First, the correlation among electron spins was measured at the absolute temperature 0.3 K (Fig.2, left). The result remarkably agrees with a theoretical calculation based on the quantum spin ice model (Fig.2, middle). It reveals such a ridge structure that the scattering intensity strongly depends on the scattering direction, unlike a peak structure to be observed around a transition temperature in conventional magnets (Fig.2, right). This indicates that monopoles become fractionalized from electron spins slightly above the transition temperature in $\text{Yb}_2\text{Ti}_2\text{O}_7$. Below 0.21 K, a typical scattering pattern indicating a magnetic ordering and a total loss of the polarization of the neutron spins were observed, confirming that the material becomes ferromagnetic. It was also found that at 0.03 K, much lower than the transition temperature, ordered spins pointed to directions that were largely rotated from the "in" or "out" allowed for spin ice. This structure of spin ordering coincides with the theoretical calculation on the same quantum spin ice model at absolute zero temperature. These observations point to a transition due to the quantum-mechanics acting on monopoles, from a magnetic Coulomb liquid where monopoles interact with each other through a Coulomb force analogous to the electric Coulomb force, to a ferromagnetic Higgs phase where the monopoles are condensed (Fig.3).

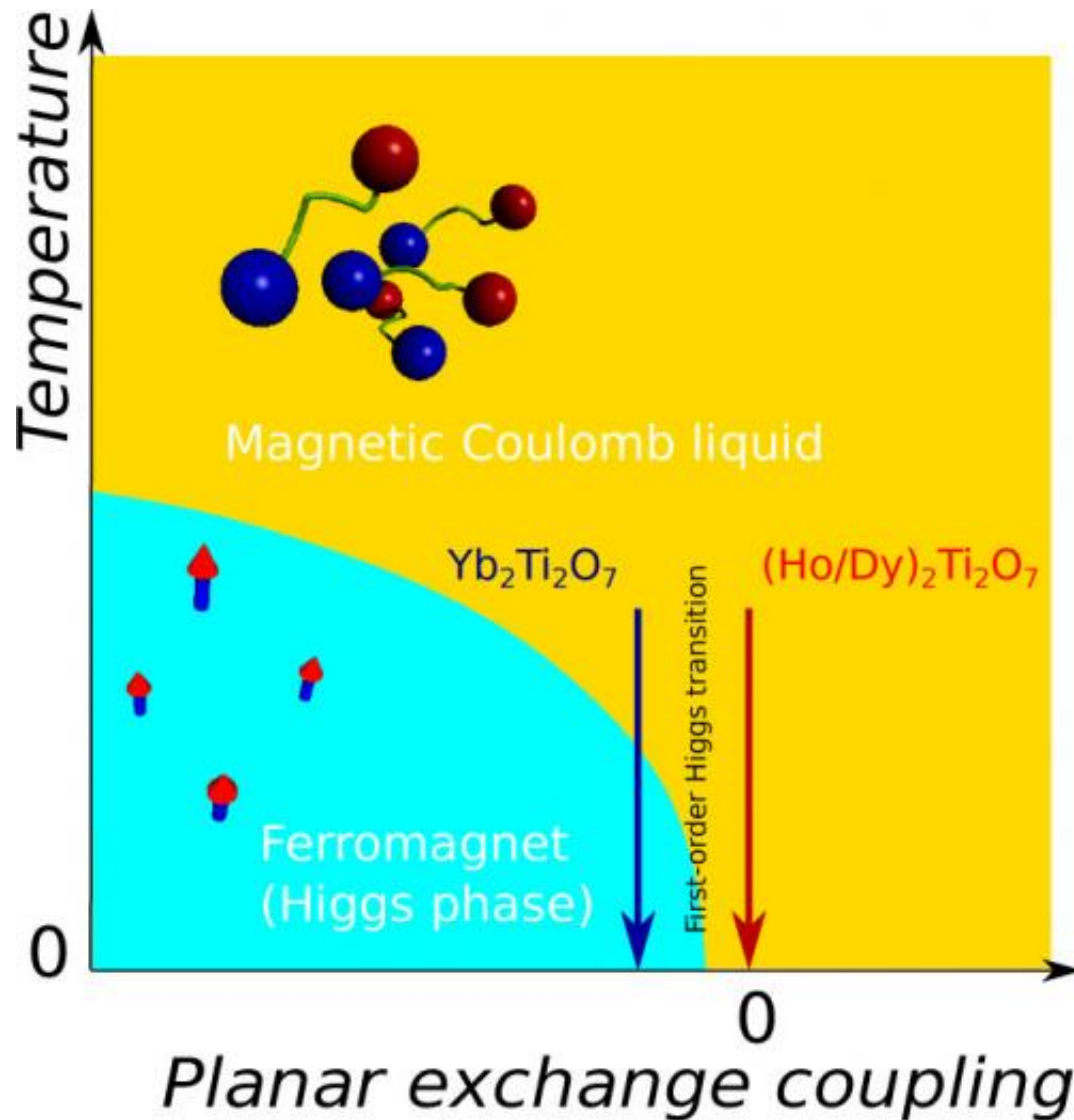


Figure three shows a schematic phase diagram of quantum spin ice. Spin ice materials, $\text{Ho}_2\text{Ti}_2\text{O}_7$ and $\text{Dy}_2\text{Ti}_2\text{O}_7$, (a red arrow) are considered to behave as a classical Coulomb liquid and the quantum nature of spins can be ignored. A quantum spin ice material $\text{Yb}_2\text{Ti}_2\text{O}_7$ (a blue arrow) undergoes a phase transition to ferromagnetic Higgs phase because of a weak quantum nature of spins. In the magnetic Coulomb liquid regime, north poles (red balls) and south poles (blue balls) behave as fractionalized but unstable particles. In the ferromagnetic Higgs phase, north and south poles become stably condensed, tilting spins from the “in” and “out” (red arrows with blue bars). Credit: RIKEN

The [superconductivity](#) showing zero electric resistivity is used for application. The [ferromagnetism](#) in quantum spin ice reported here is expected to provide the [spintronics](#), aiming at efficient controls of the magnetism for device applications, with a new state that can carry monopole current of spins without loss. [Quantum spin](#) ice materials, if the Higgs transition temperature is increased to a room temperature, may open a revolutionary industrial engineering.

More information: Lieh-Jeng Chang, Shigeki Onoda, Yixi Su, Ying-Jer Kao, Ku-Ding Tsuei, Yukio Yasui, Kazuhisa Kakurai and Martin Richard Lees. "Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $\text{Yb}_2\text{Ti}_2\text{O}_7$." *Nature Communications* 3:992 (2012), [DOI: 10.1038/ncomms1989](#)

Provided by RIKEN

Citation: Higgs transition of north and south poles of electrons in a magnet (2012, August 7) retrieved 23 April 2024 from <https://phys.org/news/2012-08-higgs-transition-north-south-poles.html>

This document is subject to copyright. Apart from any fair dealing for the purpose of private study or research, no part may be reproduced without the written permission. The content is provided for information purposes only.