Quantum Water Ice

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It has been known since the pioneering work of Bernal, Fowler and Pauling that hexagonal water ice is the architype of a frustrated material - a proton-bonded network in which protons satisfy strong local constraints - the "ice rules" - but never order.

There is now a growing body of evidence, from both simulation [Drechsel-Grau and Marx, Phys. Rev. Lett. 112, 148302 (2014)] andexperiment [Bove et al., Phys. Rev. Lett. 103, 165901 (2009)], that the protons in hexagonal water ice are not merely disordered, but mobile, collectively tunnelling from one configuration obeying the ice rules to another.

However, despite enormous progress in understanding quantum effects in frustrated magnets, very little is known about what effect such collective quantum tunnelling might have on the protons in water ice.

In this talk we revisit the theory of proton correlations in hexagonal water ice, showing how the disordered state selected by the ice rules changes, once collective quantum tunnelling is taken into account.

We find that correlations are governed by a lattice-gauge theory with exactly the same structure as electromagnetism, in which the low--energy excitations of protons have the character of ``photons".

Exactly like light in hexagonal water ice, these emergent photons are birefringent, exhibiting a dispersion which depends on both the direction of propagation and polarization of the photon.

The predictions of the quantum theory are shown to be in quantitative agreement with the results of quantum Monte Carlo simulations of hexagonal water ice, and to reproduce the ``wings" of incoherent inelastic neutron scattering observed by Bove et al.

These results raise the intriguing possibility that the protons in hexagonal water ice could form a quantum liquid with many of the same properties as the quantum spin liquids sought in frustrated magnets.