Magnetic excitations: from classical spin waves to quantum entangled excitations in low-dimensional and frustrated magnetic materials

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Magnetism in solid matter is a pure quantum effect, and would not occur without the quantized nature of electronic orbitals [1-3]. This is true for all magnetic materials, even those that adopt seemingly classic ground states such as static long range order. However, the magnetic excitations can fundamentally differ depending on the nature of the magnetic materials. In long-range ordered magnetic structures, the excitations are small, wave-like perturbations of the magnetic moments away from the ordered direction carrying S=1, so-called spin waves that are not unlike phonons [1-2]. Because quantum fluctuations are strongly suppressed in a static structure, spin waves can be described by fairly classical models. Completely different are materials that contain uncoupled dimers of single-electron states carrying S=1/2 [4]. These materials feature singlet or triplet states, and thus completely preserve the quantum nature of magnetism. This is possible because the inter-dimer correlations are too weak to suppress the quantum fluctuations.

Particularly interesting are materials where quantum fluctuations can survive in the presence of strong long-range correlations, because this can lead to novel and emergent physics. Probably the best understood case is the Haldane chain, a one-dimensional arrangement of S=1 states with nearest-neighbor antiferromagnetic interactions [4], whose properties were predicted by Haldane – an achievement recognized by the Physics Nobel Prize 2016. Instead of static order, the Haldane chain adopts a quantum entangled ground state at low temperatures that is separated by an excitation gap from its excitations, and is thus extremely stable. It contains a hidden order that is difficult to measure experimentally, but whose presence can be inferred from the nature of the excitations. Such quantum entangled states have also been observed in S=1/2 antiferromagnetic chains, leading to fractional excitations carrying S=1/2, and not S=1 as magnons do. Currently intense research focuses on the materials where quantum entangled phases can be stabilized in three-dimensional magnets, and the prime candidates are strongly-frustrated magnets with a low spin quantum number.

In my two lectures, I will discuss the nature of magnetic excitations in solid materials. I will start with conceptually simple models, such as well-understood ferromagnets and antiferromagnets and discuss the properties of the spin-waves as their most important excitations. I will give an overview of how spin waves can be measured and calculated, with a particular focus on neutron scattering. I will discuss simple models of materials that preserve quantum fluctuations in the ground states – so-called quantum magnets, and explain how their excitations can be calculated. I will then discuss the properties of materials with strong correlations while preserving the quantum nature of magnetism, and give an introduction into the novel phenomena that can emerge from quantum-entangled states. This will include a discussion of low-dimensional and frustrated magnetic magnetism [4-6].

Reference:

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