Quantum magnetism

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A kagome antiferromagnet reaches its quantum plateau

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It has long been predicted that spin-1/2 antiferromagnets on the kagome lattice should feature a series of plateaus in the change of its magnetization under an applied magnetic field. A quantum plateau of this kind has now been observed experimentally.

Antiferromagnetic interactions between neighbouring electron spins make it energetically favourable for them to point in opposite directions. However, when many spins are arranged on a kagome lattice, it is not possible for all neighbours to be anti-aligned in this fashion. This phenomenon of geometric frustration makes kagome lattice materials strong candidates for realizing quantum spin liquid phases, where quantum fluctuations prevent magnetic ordering. Kagome lattices are also predicted to exhibit a series of magnetization plateaus when subject to a magnetic field (see Fig. 1a). Whereas many of the plateaus at higher magnetic field originate from the crystallization of magnons, the origin of the lowest magnetic field plateau remains controversial, with different theoretical mechanisms yielding similar results. Now, writing in *Nature Physics*, Sungmin Jeon and colleagues report the experimental observation of a magnetization plateau of quantum origin[1].

A magnetization plateau often indicates a robust magnetic state insensitive to perturbations[2]. Some magnetization plateaus can emerge even in classical spin systems. For example, a plateau at one-third of the saturation magnetization in the kagome lattice (corresponding to a state with two up-spins and one down-spin per unit cell) is stabilized by thermal fluctuations[3]. A quantum plateau state, on the other hand, is characterized by quantum entanglement of spins in the corresponding magnetic state.

We can attempt to understand the emergence of magnetization plateaus by starting from the fully polarized spins at a sufficiently strong field. Elementary excitations above this polarized state are quantum spin waves (magnons), which obey Bose–Einstein statistics and carry one fundamental unit of spin opposite to the field direction[4]. When the magnetic field is lowered below the saturation value, Bose–Einstein condensation of magnons macroscopically reduces the magnetization. When the magnon density is commensurate with the lattice, so that the magnons can be arranged evenly across the lattice sites, a combination of kinetic frustration due to the lattice geometry and minimization of the repulsive interaction of the magnons leads to the formation of magnon crystals that manifest as magnetization plateaus[4].

Crystallization of magnons in a kagome quantum antiferromagnet involves the localization of magnons on one-third of the hexagons, giving rise to a tripled unit cell (see Fig. 1b). The six spins of a hexagon

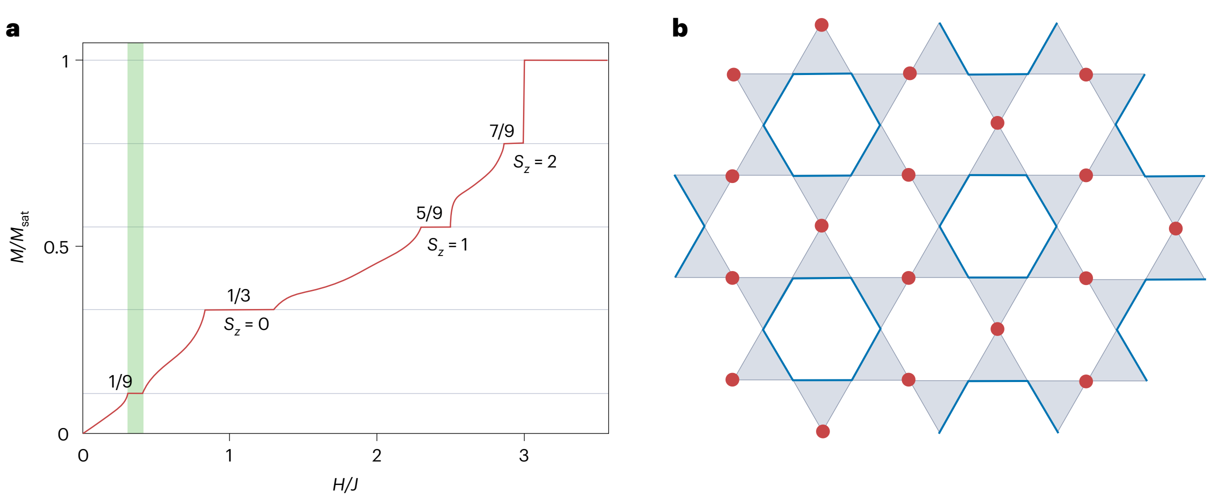

Fig. 1 | Magnetization plateaus in a kagome lattice. a, Magnetization curve of a spin-1/2 kagome antiferromagnet in a magnetic field. The magnetization M is normalized by the saturation value M_{sat}. The applied magnetic field H is measured in units of the nearest-neighbour magnetic exchange interaction J. **b**, A schematic diagram of the crystallization of hexagonal magnons (shown as blue hexagons) in a background of upward-pointing spins, indicated by red dots. The grey triangles highlight the underlying kagome lattice, which can be viewed as a network of corner-sharing triangles. The total spin of each blue hexagon is $S_z = 2, 1$ and 0 for the 7/9, 5/9 and 1/3 magnetization plateaus, respectively. In all three cases, the hexagonal magnons form an enlarged triangular lattice. The 1/9 plateau observed by Jeon and colleagues[1] has no semi-classical interpretation.

hosting the localized magnons are in an entangled state. The plateau states with a magnetization of 7/9, 5/9 and 3/9 the saturation value correspond to localization of exactly one, two and three magnons, respectively, in the resonating hexagons[5,6]. These plateau states are robust as they are also predicted to exist in kagome antiferromagnets with localized magnetic moments larger than spin-1/2 (ref. 7).

When each lattice site features spin-1/2 magnetic moments, the six spins of a hexagon can host at most three magnons, indicating that a 1/9 plateau state cannot be achieved using the simple picture of hexagonal magnons described above. However, numerical calculations of the spin-1/2 kagome antiferromagnet including quantum effects have predicted that a 1/9 magnetization plateau does exist, contrary to expectations from the semi-classical magnon picture[5–8]. It is this plateau that has now been observed by Jeon and colleagues at a temperature of 0.5 kelvin when the magnetic compound $YCu_3(OD)_{6+x}Br_{3-x}$ is subjected to an external magnetic field.

Unlike previously studied kagome compounds, such as herbertsmithite, which suffer from detrimental disorder in the form of mixing between zinc and copper atoms, $YCu_3(OD)_{6+x}Br_{3-x}$ is nearly free of additional 'orphan' magnetic moments induced by site disorder. Through a series of measurements of characteristics including specific heat, thermal conductivity, and Raman scattering, the team found that the low-energy behaviour of this kagome antiferromagnet can best be attributed to quasi-particles with a Dirac-like nodal structure, suggesting that a gapless quantum spin liquid may be the material's ground state at zero external magnetic field.

It is worth noting that the 1/9 plateau exists only when the magnetic field is applied perpendicularly to the kagome plane. The width of the plateau as well as the strength of the critical fields that stabilize the 1/9-plateau state agree well with state-of-the-art theoretical calculations. However, in the presence of an in-plane magnetic field the magnetization exhibits a shoulder-like feature in the field range of the expected 1/9 plateau. This suggests that a noticeable anisotropy exists in the magnetic properties of $YCu_3(OD)_{6+x}Br_{3-x}$. Moreover, anomalies in the low-temperature thermodynamical behaviour are ascribed by the authors to a quenched disorder in the compound's chemical bonds. The 1/9-plateau state stabilized by a perpendicular field is robust against both these perturbations.

Early numerical calculation suggested that the 1/9-plateau state is a gapped quantum spin liquid and thus topologically different from both the gapped and gapless spin liquids that are proposed to be the zero-field ground state of the spin-1/2 kagome antiferromagnet[5]. Later theoretical work, on the other hand, associated the quantum plateau with a valence-bond crystal, which is characterized by a periodic modulation of correlations between nearest-neighbour spin pairs[7–9]. Because these two magnetic phases are expected to respond differently to perturbations such as anisotropy and disorder in magnetic interactions, the experiment of Jeon and colleagues could help researchers to clarify the nature of the quantum 1/9-plateau state in kagome antiferromagnets.

The theoretical controversy surrounding this unusual 1/9 magnetization plateau in an applied magnetic field is reminiscent of the debate regarding the nature of the zero-field quantum spin liquid. Indeed, even though a valence-bond crystal ground state has been obtained in several recent numerical calculations for the 1/9 plateau[7–9], researchers disagree on the pattern of the bond modulations. The near degeneracy of the various proposed wavefunctions in both cases could be due to the intrinsic complexity and highly frustrated nature of kagome systems. Experimental results from new kagome compounds such as $YCu_3(OD)_{6+x}Br_{3-x}$ thus provide a valuable opportunity to develop a coherent theoretical picture of the kagome lattice antiferromagnet, one of the most important models in quantum magnetism.

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Competing interests

The author declares no competing interests.