Possible observation of quantum spin-nematic phase in a frustrated magnet

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Water freezes into ice in winter and evaporates into vapor in summer. Scientifically, the transformations between solid, liquid, and gas are called phase transitions and can be classified through the changes in symmetry which occur in each case. A fourth phase of matter was discovered late in the 19th century: the liquid crystal nematic, in which rod- or disk-shaped molecules align like the atoms in a solid, while continuing to flow like a liquid. Here we report thermodynamic evidence of a quantum analog of the classical nematic phase, the quantum spin nematic (SN). In an SN, the spins of a quantum magnet select a common axis, like a nematic liquid crystal, while escaping conventional magnetic order. Our state-of-the-art thermal measurements in high pulsed magnetic fields up to 33 T on the copper mineral volborthite with spin 1/2 on a frustrated lattice provide thermodynamic evidence for SN order, half a century after the theoretical proposal [Blume M, Hsieh YY (1969) J Appl Phys 40:1249; Andreev AF, Grishchuk IA (1984) J Exp Theor Phys 97:467–475].

significance

Spin-nematic state in frustrated ferromagnet is one of the exotic states of matter at high magnetic field that could arise as the Bose–Einstein condensation of the two-magnon bound state. Its experimental detection in a real material has long been hindered by the fact that the order parameter of the spin-nematic state, spin quadrupole moment, is hard to detect with conventional magnetic probes available in high magnetic field. Here we design a calorimeter for the pulsed magnetic field studies and perform state-of-the-art measurements of heat capacity and magnetocaloric effect up to 33 T. These results provide strong prima facie evidence for a spin-nematic state in the copper-based mineral volborthite.

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resolved, and a second from 25 distinct phases approaching the magnetization plateau, here labeled N1 and N2; we identify phase N2 as an SN. At lower values of magnetic field, volborthite quadrupole moments on first-neighbor bonds (green lozenges). The thermodynamic measurements reported in this article make it possible to distinguish two can be viewed as a polarized state (P) of spins on a square lattice. The condensation of bound pairs of magnons would lead to the formation of a SN with saturates, giving rise to a broad plateau in magnetization. (Inset) Energy of one- and two-magnon excitations, relative to the field-polarized state (P), as a function of magnetic field (H). The SN state is formed through the condensation of bound pairs of magnons (9–11). This occurs when the magnetic field falls below a critical field determined by the two-magnon binding energy (H_p). SN order occurs when H_p is greater than the critical field for condensation of a single magnon (H). Parallel NMR experiments (20, 21) provide valuable information about magnetic correlations. Within the magnetization plateau, ^35^V NMR presents a single sharp line, consistent with a uniform distribution of internal fields, at an energy independent of magnetic field. Meanwhile, for 4.5 < H < 22.5 T (phase II in Fig. 2C), NMR reveals a broad distribution of internal fields, bounded by two distinct peaks, characteristic of a spin-density wave (SDW) state. For intermediate fields 22.5 < H < 27.5 T, magnetization increases sharply, and the ^35^V NMR line undergoes a complex evolution, which is not consistent with either an SDW or conventional magnetic order. This evolution can be divided into two regimes, one from 22.5 < H ≤ 25 T, where two peaks are resolved, and a second from 25 < H < 27.5 T, where the NMR line shape shows the same structure as in the 1/3 plateau, with a single sharp peak. In this sense, the situation closely parallels that in LiCuVO_4, where the NMR line shape in the proposed SN phase resembles that in the saturated state, and the combination of magnetization, NMR, and theoretical prediction together build a strong case for SN order (16). The remaining challenge, in both cases, is to find clear thermodynamic evidence for a new phase. To get insight on the possible SN order in volborthite, we have carried out heat capacity (C) and magnetocaloric effect (MCE) measurements under pulsed magnetic fields up to 33 T. These thermodynamic quantities relate to entropy and are sensitive to any phase transition irrespective of the type of order parameter (22). A good demonstration is found for the hidden order of URu_2Si_2, which can be clearly detected by heat capacity and MCE, whereas most other techniques fail (23). However, measuring heat capacity for magnetic compounds under a pulsed magnetic field varying in a short time duration of milliseconds is challenging because the field variation causes temperature

**Fig. 2.** Microscopic model and experimental magnetization curve of volborthite. (**A**) Spin-1/2 Cu^{2+} ions within volborthite (red and blue disks) occupy the sites of a kagome lattice with highly anisotropic exchange interactions. These moments form trimers, which act as a single effective spin-1/2 moment, with trimers centered on a regular array of lattice sites (red circles). (**B**) The network of trimers within volborthite forms a square lattice of effective spin-1/2 moments (black arrows), with competing ferromagnetic first-neighbor interactions (J_1) and antiferromagnetic second-neighbor interactions J_2 and J_2’. (**C**) Magnetization curve of volborthite, measured at 1.4 K, in pulsed fields of up to 75 T (20). At a critical field of 27.5 T, the magnetization of the spin-1/2 trimers saturates, giving rise to a broad plateau in magnetization. (Inset) Detail of magnetization for H – 30 T, showing the onset of the magnetization plateau. This can be viewed as a polarized state (P) of spins on a square lattice. The condensation of bound pairs of magnons would lead to the formation of a SN with quadrupole moments on first-neighbor bonds (green lozenges). The thermodynamic measurements reported in this article make it possible to distinguish two distinct phases approaching the magnetization plateau, here labeled N1 and N2; we identify phase N2 as an SN. At lower values of magnetic field, volborthite exhibits phase transitions into an incommensurate SDW (II) and an unidentified low-field phase (I).
fluctuation owing to MCE. We have developed a state-of-the-art technique to generate a modified pulsed magnetic field with its top truncated to become almost flat with a high field stability of \(\pm 0.01\) T, which allows us to measure heat capacity precisely at the flat-top field down to 0.8 K.

We first discuss the phase boundaries found using MCE measurements and then use corresponding result for heat capacity to characterize each of the phases found. Fig. 3A shows the evolution of curves of constant entropy, \(T(H)\), taken from MCE measurements performed under quasi-adiabatic conditions (A-MCE), starting from the state found for \(H = 0\) at a given temperature. In all cases the adiabat \(T(H)\) initially decreases with increasing field, before passing through a broad minimum at \(H \sim 25\) T and then increasing, behavior consistent with a phase transition at low temperatures (22). Adiabats become tightly bunched at low temperatures, approaching the onset of the 1/3-magnetization plateau \(P\) at \(H_{P} \sim 27.5\) T, suggesting a dense set of low-energy excitations (22). A notable change occurs when the temperature falls below \(\sim 1.7\) K; the broad minimum in \(T(H)\) acquires small dips, indicative of phase transitions, at \(H_{s1} \sim 22.5\) T and \(H_{s2} \sim 25.5\) T and \(H_{P} \sim 27.5\) T. Each of these three critical fields is singled out by a corresponding anomaly in measurements of MCE under approximately isothermal conditions (1-MCE) of \(T = 1.25, 1.0,\) and 0.75 K (Fig. 3B) and the related changes in entropy (Fig. 3C). Together with measurements of heat capacity, discussed below, these results clearly delineate two domes in the \((H,T)\) plane, each corresponding to a different low-temperature phase. We label these phases \(N_{1}\) and \(N_{2}\) in Fig. 3; \(N_{1}\) corresponds to the phase \(N\) found in earlier NMR experiments (20, 21), and \(N_{2}\) fills the gap between \(N\) and \(P\).

We now turn to measurements of heat capacity, which provide more insight into the nature of the phases \(N_{1}\) and \(N_{2}\). Fig. 4 shows the temperature dependence of heat capacity for magnetic field ranging from 0 to 30.2 T. In the absence of magnetic field, \(C(T)\) exhibits small peaks at 0.8 and 1.2 K, as reported previously (24) (Fig. 4A). The onset of SDW order (II) at intermediate values of magnetic field is revealed in broad shoulders in \(C(T)\): these occur at \(T \sim 2\) K for \(H = 14\) T and \(T \sim 1.5\) K for \(H = 20.4\) T (Fig. 4A), in agreement with phase boundaries found in NMR (24). Very different behavior is observed for \(H > H_{P}\): the transition into the phase \(N_{1}\) is marked by a substantial \(\lambda\)-shaped anomaly, occurring at \(T \sim 1.54\) K for \(H = 22.8\) T, in agreement with the phase boundary identified in MCE (Fig. 3). This feature becomes still more pronounced with increasing field (Fig. 4A). Meanwhile, the onset of the phase \(N_{2}\) is accompanied by an extremely sharp peak, consistent with a logarithmic divergence in \(C(T)\) (Fig. 4B). The crossover into the saturated state, for \(H > H_{P}\), is not accompanied by any anomaly in \(C(T)\) (Fig. 4B). These results provide unequivocal evidence that \(N_{1}\) and \(N_{2}\) are bulk, thermodynamic phases; we find corresponding changes in entropy of \(\Delta S = 0.12\) Rn2 entering phase \(N_{1}\) at \(H = 24.2\) T and \(\Delta S = 0.09\) Rn2 entering phase \(N_{2}\) at \(H = 26.3\) T.

Spontaneous symmetry breaking can produce a gapless Goldstone excitation that gives power-law behavior in the low-temperature heat capacity. For most ordered states including SDW and SN states, one would expect linearly dispersing Goldstone modes (8, 12, 25). These usually contribute to the low-temperature heat capacity as \(C(T) \propto T^{d}\), where \(d\) is the spatial dimension of the system. As shown in the log-log plots of Fig. 4C and D, the low-temperature heat capacities for phases I and II tend to be proportional to \(T^{d}\), while for phases \(N_{1}\) and \(N_{2}\), \(C(T) \propto T^{3}\). This implies that the character of magnetic excitations changes from 3D to 2D, although it is preferable to increase the temperature range of the fit (SI Appendix). Probably, for phases I and II, 3D antiferromagnetic magnons or phasons occur (8) owing to non-negligible interlayer couplings, while the dimensionality of magnetic excitations for phases \(N_{1}\) and \(N_{2}\) is qualitatively reduced in the measurement temperature range. This type of dimensional reduction is not surprising in a quasi-2D magnet with SN order, since the opening of a gap to transverse spin excitations will lead to a suppression of interplane exchange.

In the state \(P\), for \(H > H_{P}\), there is no phase transition above 0.8 K, and the low-temperature heat capacity shows exponentially activated behavior (Fig. 4E): the 30.2 T data are well described by the equation, \(C = \exp[-\Delta/k_{B}T]/T\) (26), with an activation energy \(\Delta = 6.7\) K. We interpret this as a gap to two-magnon excitations, as illustrated in Fig. 1B (19). Assuming that this gap opens at \(H_{P} = 27.5\) T and modeling it as \(\Delta = g_{\mu B}(H - H_{P})\), we arrive at an effective Landé \(g\) factor of \(g = 3.7\). It should be noted that the critical field deduced from the phase boundary, \(H_{P} = 30.2\), lies in the range 27.5–28.0 T, which yields \(g = 3.7–4.5\) (SI Appendix). These values are nearly twice as large as the single-electron \(g\) factor found in electron spin resonance measurements at lower values of field (\(g_{e} = 2.04\) below 12 T (27)), consistent with a two-magnon excitation. The \(g\) factor estimated from NMR measurements on volborthite also shows an enhancement to \(g \sim 4.6–5.9\) (24), providing further evidence for two-magnon bound states.

To recap, it has been suggested (19) that for a narrow range of \(H\) just below \(H_{P}\), bound pairs of magnons undergo a low-temperature BEC, leading to an antiferroquadrupolar SN order, as illustrated in Fig. 2C. At present the case for this SN order rests on a combination of theoretical analysis of the crystal structure and associated magnetic model (19) and NMR experiments which,
for the phase N2, are incompatible with any conventional form of magnetic order (20, 21). The thermodynamic measurements reported in this manuscript supply the missing pieces of this puzzle.

The first crucial piece of evidence comes from the field dependence of the excitation gap with the 1/3-magnetization plateau, P. From measurements of heat capacity, we can identify the lowest-lying excitation within P as a two-magnon bound state, with gap which tends to zero approaching the transition into the phase N2 (Fig. 4E). This result explicitly links the mechanism identified in theory—the condensation of two-magnon bound states (9, 19)—to the phase transition observed in experiment, at low temperatures, as a function of magnetic field.

The second crucial result is clear evidence for a thermodynamic phase transition into the phase N2, at finite temperature and fixed magnetic field (Fig. 4B). This phase transition, which separates the high-temperature paramagnet from a low-temperature, broken-symmetry state, appears to be continuous, with a vanishingly small critical exponent, as found for, e.g., 3D-XY or 2D-Ising universality classes. [We note that an Ising transition is expected for an SN in the presence of Dzyaloshinskii–Moriya interactions (8).]

The third distinct piece of evidence comes from measurements of heat capacity at low temperatures for fixed magnetic field, within the phase N2. The power-law behavior of heat capacity at low temperature provides clear evidence for the emergence of a Goldstone mode, associated with the breaking of spin rotation symmetry within phase N2 (Fig. 4D). Under other circumstances, such a Goldstone mode could be explained by conventional magnetic order. However, this is ruled out by published NMR results (20, 24), which fail to find the internal field associated magnetic order. The onset of N2 is distinguished by a sharp peak in C(T) for T ~ 1.5 K. This form of the peak is consistent with the logarithmic divergence expected for an Ising phase transition in 2D. Both phases exhibit a T² scaling of heat capacity at low temperatures, consistent with a linearly dispersing excitation in 3D. This form of dimensional reduction is expected for weakly coupled 2D SNs. (E) Heat capacity of magnetization plateau P, showing activated behavior at low temperatures, consistent with the opening of a gap Δ = 6.7 K at 30.2 T.

Our thermodynamic measurements also clearly identify a second new phase N1, which is distinct in its properties from N2. The nature of this phase remains an open question, and at this point it is only possible to speculate as to its origin. The phase N1 shares a number of features with N2, including a sharp singularity in heat capacity at the ordering temperature and a T² behavior at low T. However, the NMR spectra of phase N1 contain multiple peaks, which is different from the single-peak feature in N2, indicating the presence of an internal field in N1 (20, 24). One possible explanation for this would be a heterogeneity in the crystal (24), but this seems hard to reconcile with the sharpness of the phase transition or the single peak found in phase N2. An intriguing alternative is the microscopic coexistence of a dipolar SDW and a quadrupolar SN order. It is already known that SDW and SN correlations coexist in the high-field states of frustrated ferromagnetic spin chains (5, 6). Any ordered phase in which both were present would break translational symmetry, through S' (SDW), making it a solid, and spin-rotation symmetry, through the transverse quadrupole moments Qx and Qy (SN), making it a superfluid (9, 19). In this sense the phase N1 could be a supersolid, a state long sought in 4He (28) and also widely discussed in the context of frustrated magnets. The data available for volborthite seem consistent with this interpretation of the phase N1, but further experimental and theoretical work will be needed to establish its validity.

In summary, in this article we have presented a detailed study of the thermodynamic properties of the frustrated magnetic insulator volborthite, in high magnetic field. These results are summarized in the phase diagram, Fig. 3. We find evidence for the existence of two magnetic phases, labeled N1 and N2, at fields approaching the known 1/3-magnetization plateau, P. The thermodynamic properties of the phase N2, and its previously reported NMR line shape (21), appear to be consistent with the published prediction of SN order (19).

We note that while this article was under review, two studies have also reported the possibility of SN order in the square-lattice frustrated ferromagnet BaCdVO(PO4)2 (29, 30).

**Methods**

Materials. Single crystals of volborthite Cu3V2O7(OH)2·2H2O were grown by the hydrothermal method (31). CuO (99.99%, 6.0 g) and V2O5 (99.99%, 3.0 g) powders were mixed in the stoichiometric ratio and were put into a Teflon container together with 1.1 wt% nitric acid (400 mL). Then, the container was placed in a stainless steel vessel and heated to 443 K for 30 d and furnace-cooled to room temperature. Single crystals of volborthite thus obtained are transparent yellow–green, arrowhead shaped, and typically 1 x 0.5 x 0.05 mm in size. They crystallize in the monoclinic C2/c structure at room temperature. Upon cooling, two structural transitions take place to the I2/m structure at 290 K and to the P2₁/a structure at 155 K (31). Thus, the

Fig. 4. Heat capacity and thermodynamic evidence for low-energy excitations volborthite. (A) Experimental results for heat capacity C(T), for magnetic fields spanning the low-field phase I, SDW phase II, and phase N1. The onset of N1 is distinguished by a sharp anomaly in C(T) for T ~ 1.5 K. (B) Heat capacity within the hidden-order phase N2 and magnetization plateau P. The onset of N2 is distinguished by a sharp peak in C(T) for T ~ 1.4 K. The form of this peak is consistent with the logarithmic divergence expected for an Ising phase transition in 2D. (C) Heat capacity for phases I and II, plotted on a log–log scale. Both phases exhibit a T² scaling of heat capacity at low temperatures, consistent with a linearly dispersing excitation in 3D. This form of dimensional reduction is expected for weakly coupled 2D SNs. (E) Heat capacity of magnetization plateau P, showing activated behavior at low temperatures, consistent with the opening of a gap Δ = 6.7 K at 30.2 T.
crystal structure of volborthite at low temperatures concerned in the present study is the P2_1/a structure (supplemental material in ref. 20). In this structure, there are two kinds of crystallographically distinguished kagome layers instead of one kind in the 22/m structure. However, the two kagome layers have an identical arrangement of spin-carrying Cu 3d_{x^2−y^2} orbitals and nearly equal bond lengths and angles, suggesting that the magnetic interactions there may be almost the same. In fact, the DFT + U calculations suggest nearly equal magnetic interactions for the two layers (19).

**MCE.** To determine the H-T phase diagram, we performed MCE experiments in a pulsed magnetic field up to 33 T in two different conditions: one is an adiabatic condition (A-MCE), and the other is a nearly isothermal condition in a pulsed magnetic field up to 33 T in two different conditions: one is a constant temperature (32). The I-MCE data are converted to entropy change measurements in the nearly isothermal condition. Compared with A-MCE, I-MCE reveals the induced phase transitions.

\[
\Delta S = \frac{\Delta C}{T} \ln \left( \frac{M}{\Delta M} \right),
\]

where \( S, M, \) and \( C \) are entropy, magnetization, and heat capacity, respectively. (22). Thus, the \( T(H) \) curve is sensitive to any magnetic phase transition. This has been demonstrated for Sr_3Ru_2O_7 (32), where multiple kinks in the \( T(H) \) curves are observed and successfully attributed to a series of field-induced phase transitions.

To decide a phase boundary at lower temperatures, we carried out I-MCE measurements in the nearly isothermal condition. Compared with A-MCE, I-MCE is less sensitive to phase boundaries but can be performed at lower temperatures. Moreover, it yields the field dependence of entropy at an almost constant temperature (32). The I-MCE data are converted to entropy change \( \Delta S(M) \) by the equation \( \Delta S = \int (T−T_0)\,dT \), where \( T_0 = \) the thermal conductance between the sample and the surrounding thermal bath and \( T_0 \) is the temperature of the thermal bath. Assuming a constant value of \( k_\text{B} \), the field dependence of \( \Delta S \) is estimated in the arbitrary unit and plotted in Fig. 3C.

**Heat Capacity Measurements at Flat-Top Pulsed Magnetic Fields.** Heat capacity measurements under high magnetic fields above 20 T are not possible in commercial equipment. Either static fields using a big facility or pulsed fields with short time duration are necessary to generate larger magnetic fields. We have employed the latter, but measuring heat capacity in a quickly varying magnetic field with short time duration are necessary to generate larger magnetic fields. We have applied this state-of-the-art technique to study the crystal structure of volborthite at low temperatures concerned in the present study is the P2_1/a structure (supplemental material in ref. 20). In this structure, there are two kinds of crystallographically distinguished kagome layers instead of one kind in the 22/m structure. However, the two kagome layers have an identical arrangement of spin-carrying Cu 3d_{x^2−y^2} orbitals and nearly equal bond lengths and angles, suggesting that the magnetic interactions there may be almost the same. In fact, the DFT + U calculations suggest nearly equal magnetic interactions for the two layers (19).

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