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# Magnetic Excitations and Continuum of a Possibly Field-Induced Quantum Spin Liquid in $\alpha$ -RuCl<sub>3</sub>

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We report on terahertz spectroscopy of quantum spin dynamics in  $\alpha$ -RuCl<sub>3</sub>, a system proximate to the Kitaev honeycomb model, as a function of temperature and magnetic field. We follow the evolution of an extended magnetic continuum below the structural phase transition at  $T_{s2} = 62$  K. With the onset of a long-range magnetic order at  $T_N = 6.5$  K, spectral weight is transferred to a well-defined magnetic excitation at  $\hbar\omega_1 = 2.48$  meV, which is accompanied by a higher-energy band at  $\hbar\omega_2 = 6.48$  meV. Both excitations soften in magnetic field, signaling a quantum phase transition close to  $B_c = 7$  T, where a broad continuum dominates the dynamical response. Above  $B_c$ , the long-range order is suppressed, and on top of the continuum, emergent magnetic excitations evolve. These excitations follow clear selection rules and exhibit distinct field dependencies, characterizing the dynamical properties of a possibly field-induced quantum spin liquid.

Quantum spin liquids (QSLs) are exotic states of matter in which quantum fluctuations prevent conventional magnetic long-range order even at the lowest temperatures. The ground states of QSLs are highly-entangled and albeit disordered, can exhibit well-defined quasiparticles which are non-local and fractionalized [1, 2]. The Kitaev honeycomb model [3] is a representative example for the existence of a QSL, which hosts fractionalized Majorana fermions and flux excitations. Moreover, bound states of the fractional excitations and excitations of non-Abelian type can occur when the time-reversal symmetry is broken [4–6], e.g., by applying an external magnetic field. As this model is exactly solvable and thus provides quantitative understanding for the ground state as well as for the dynamical response of the QSL [3, 7], significant experimental efforts have been undertaken to realize the QSL and to search for its unconventional excitations.

Strong spin-orbit couplings together with a proper crystal electric field are important ingredients for realizing the Kitaev honeycomb model in magnetic insulators [8]. Based on  $5d$  or  $4d$  ions with strong spin-orbit coupling, a Mott insulator with an effective spin-1/2 localized on a honeycomb lattice has been realized in the iridates [9] and recently in  $\alpha$ -RuCl<sub>3</sub> [10–14]. In  $\alpha$ -RuCl<sub>3</sub>, besides the significant Kitaev term [15, 16] that accounts for bond-dependent Ising exchange, other interactions, especially Heisenberg and off-diagonal exchange interactions, have been suggested to be responsible for the magnetic zigzag order below  $T_N = 6.5$  K and for the observed sharp spin-wave-like excitations [17–22].

To realize a QSL in  $\alpha$ -RuCl<sub>3</sub>, obviously the long-range zigzag order has to be suppressed, e.g. by tuning the external parameters, such as pressure [23, 24] or magnetic field [11, 25–29]. When the external magnetic field is

applied in the crystallographic  $ab$  plane of  $\alpha$ -RuCl<sub>3</sub>, the magnetic zigzag order is suppressed at about  $B_c = 7$  T, with the emergence of a field-induced disordered phase, a putative QSL well below the fully polarized state. However, whether the elementary spin excitations are gapped or gapless, which is important for characterizing a QSL [1], is still under debate for the field-induced disordered phase in  $\alpha$ -RuCl<sub>3</sub> [27, 28], since a direct measurement of the magnetic excitations in the disordered phase so far has not been performed. Moreover, the existence of exotic quasiparticles is yet to be proven for the time-reversal symmetry-broken phase in applied magnetic fields.

Here, by performing terahertz (THz) spectroscopy as a function of temperature and magnetic field, we are able to directly reveal the quantum spin dynamics in the different phases of  $\alpha$ -RuCl<sub>3</sub>. We resolve a magnetic continuum at zero field, the evolution of which is followed below the structural phase transition at  $T_{s2} = 62$  K. Across the magnetic ordering temperature  $T_N = 6.5$  K, the spectral weight of the continuum is partially shifted to two magnetic excitations. As a function of magnetic field applied in the crystallographic  $ab$  plane, we provide spectroscopic evidence for a field-induced quantum phase transition at  $B_c = 7$  T. Approaching  $B_c$  from below, the two magnetic excitations soften and we observe a remarkably broad continuum just at the critical field. Above  $B_c$ , magnetic excitations evolve out of the continuum, signaling the opening of a spin gap. The hierarchy and distinct field dependencies of the emergent excitations characterize the dynamical properties, which could be viewed as a signature of many-body interactions and/or bound states of fractionalized excitations [4–6] in the possibly field-induced QSL. Our experimental results also reveal a clear polarization dependence of these excitations, establishing a comprehensive characterization of

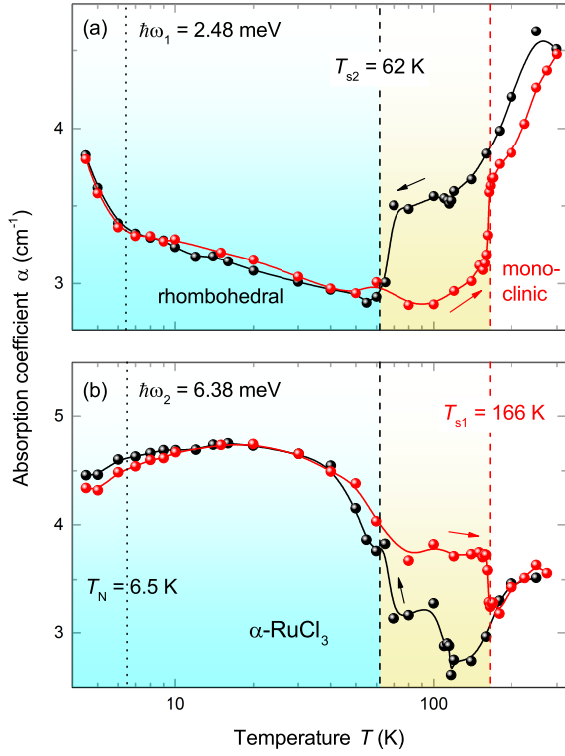


Figure 1. Absorption coefficient  $\alpha$  as a function of temperature  $T$  for the photon energies (a)  $\hbar\omega_1 = 2.48$  meV and (b)  $\hbar\omega_2 = 6.38$  meV, respectively, measured with the THz wave vector perpendicular to the crystallographic  $ab$  plane of  $\alpha$ -RuCl<sub>3</sub>. Clear hysteresis is revealed at the structural phase transitions between the low-temperature rhombohedral and the high-temperature monoclinic phases. Solid lines are guides for the eyes. The structural phase boundaries [14] are indicated by the dashed lines at  $T_{s2} = 62$  K and  $T_{s1} = 166$  K, and the magnetic phase transition by the dotted line at  $T_N = 6.5$  K.

the quantum spin dynamics of the QSL.

High-quality single crystals of  $\alpha$ -RuCl<sub>3</sub> were grown using a vacuum sublimation method [16] and have been characterized by various techniques [14, 25, 30, 31]. The samples for the optical experiments have a typical  $ab$  surface of  $5 \times 3$  mm<sup>2</sup> and a thickness of about 1 mm. To study the temperature dependent optical response, time-domain THz transmission measurements were performed with the THz wave vector  $\mathbf{k}$  perpendicular to the crystallographic  $ab$  plane, for 4 – 300 K in the effective spectral range 1.5 – 9 meV using a TPS Spectra 3000 spectrometer (TeraView Ltd.). Time domain signals were obtained for references (empty apertures) and samples, from which the power spectra were evaluated via Fourier transformation [33, 34]. Field dependent THz absorption experiments were carried out at 2.4 K in Voigt configuration, i.e.  $\mathbf{k} \perp \mathbf{B}$ , with a magneto-optic cryostat equipped with a 17 T superconducting magnet. The absorption spec-

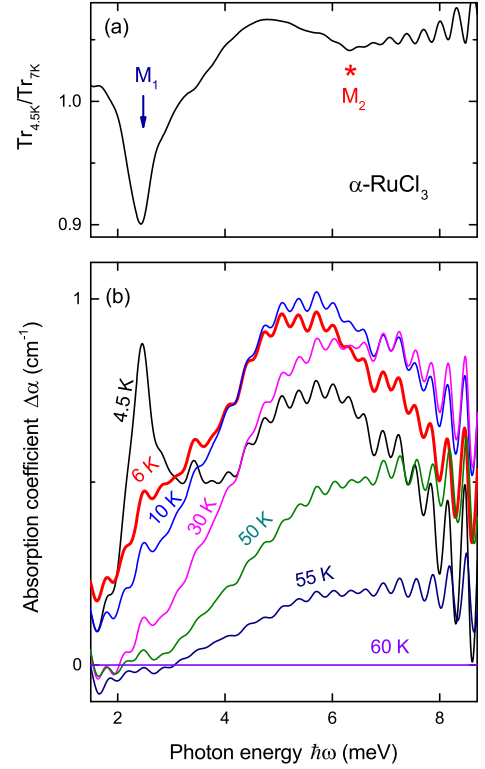


Figure 2. (a) Ratio of transmission as obtained at 4.5 K ( $T < T_N$ ) and 7 K ( $T > T_N$ ) as a function of photon energy in  $\alpha$ -RuCl<sub>3</sub>. Two dips appear below  $T_N = 6.5$  K at  $\hbar\omega_1 = 2.48$  meV (mode  $M_1$ ) and  $\hbar\omega_2 = 6.38$  meV (band  $M_2$ ), as marked by the arrow and asterisk, respectively. (b) Evolution of absorption-coefficient spectra with decreasing temperature below  $T_{s2}$ , where the 60 K spectrum is taken as a reference. A broad continuum extending over the whole spectral range evolves with decreasing temperature down to  $T_N$ . Below  $T_N$ , the spectral weight transfers to lower frequency with a sharp peak developing at  $\hbar\omega_1$ . The oscillations are due to multiple interference at the sample surfaces.

tra were recorded using a Sciencetech SPS200 Martin-Puplett type spectrometer with a 0.3 K bolometer and a rotatable polarizer in front of the sample.

The THz response of  $\alpha$ -RuCl<sub>3</sub> exhibits a very anomalous temperature dependence. Figure 1 shows the absorption coefficient as a function of temperature measured by heating and cooling the sample, for the photon energies  $\hbar\omega_1 = 2.48$  meV and  $\hbar\omega_2 = 6.38$  meV [see Fig. 2(a)]. For both frequencies we observe a markedly strong hysteresis between the heating and cooling curves for the temperature range from  $T_{s2} = 62$  K to  $T_{s1} = 166$  K, which reflects the structural-phase transitions between the high-temperature monoclinic and the low-temperature rhombohedral phases [14, 27, 30, 31].

THz spectroscopy is sensitive to dynamical response in the vicinity of the  $\Gamma$  point, where inelastic neutron scattering experiments have revealed a broad continuum

of magnetic quasiparticles up to 120 K [16, 19]. The evolution of this continuum with temperature was compared to an expected temperature dependence of the continuum of fractional Majorana fermions in the Kitaev model [16, 32]. To avoid the complication of the structural fluctuations above  $T_{s2}$ , we show in Fig. 2(b) the absorption spectra below  $T_{s2}$  with the spectrum of 60 K taken as a reference. It has been indicated by other experimental techniques that below this temperature, an evident magnetic-field dependent behavior develops [27, 29]. Compared to the inelastic neutron scattering results, the THz spectroscopy reveals here a similar broad continuum extending over the spectral range up to 9 meV. With decreasing temperature the continuum develops rapidly and exhibits a broad maximum with the maximum position shifting to lower frequency. At 6 K (below  $T_N$ ), the continuum is slightly reduced and the spectral weight is transferred to an excitation appearing at about 2.5 meV. The transfer of spectral weight to lower energies becomes more evident at lower temperatures. As seen from the 4.5 K spectrum, a very sharp peak shows up at 2.48 meV, while the continuum with broad maximum at 5–6 meV is strongly suppressed. This behavior is also clearly displayed in Fig. 1. While the absorption coefficient at 2.48 meV increases below  $T_N$ , it drops slightly around 6.38 meV.

To unambiguously identify the magnetic excitations, we calculate the ratio of transmission as measured at 4.5 and 7 K, below and right above the magnetic ordering temperature  $T_N$ . As shown in Fig. 2(a), the ratio of transmission exhibits a sharp dip at 2.48 meV (mode  $M_1$ ) and a shallow minimum around 6.38 meV (band  $M_2$ ). Both modes, with frequencies comparable to the magnetic excitations determined in the inelastic neutron scattering experiments [16, 19], have been captured by recent exact-diagonalization calculations [20] of a model guided by *ab-initio* studies [21, 35–37], where in addition to the Kitaev interactions, the off-diagonal couplings were included together with the nearest- and third-neighbour Heisenberg exchange interactions. However, the nature of the two modes remains unsettled. The lower-lying mode  $M_1$  with a sharp absorption line, ascribed to the antiferromagnetic resonance in Ref. [38], corresponds to the single-magnon branch at the  $\Gamma$  point in the calculations [20]. In contrast, the band  $M_2$  at higher energies is rather broad and weak. This mode may correspond to the higher-energy mode with small intensity in the linear spin-wave theory [20]. Since  $M_1$  and  $M_2$  arise below the antiferromagnetic phase transition, they should naturally characterize the dynamical response of the zigzag order below  $T_N$ . Above  $T_N$ , the modes  $M_1$  and  $M_2$  transfer their spectral weight to the continuum as observed in the THz spectra [Fig. 2(b)]. The temperature dependence of the continuum is consistent with the results of the neutron scattering study [16, 19], which has been discussed in the context of the Kitaev honeycomb

model [19, 32]. Alternatively, since the non-Kitaev terms are also important for  $\alpha$ - $\text{RuCl}_3$  [18, 20], one may speculate that this experimentally resolved continuum could correspond to a two-magnon continuum. Following this interpretation [20], the continuum represents incoherent excitations due to strong magnetic anharmonicity. In this case single magnons are unstable due to anharmonic interaction terms and the observation of a magnetic continuum in THz spectroscopy could be understood as virtual process involving excitation and decay of single magnons.

Figures 3(a) and 3(b) show the absorption spectra as a function of an external magnetic field applied in the  $ab$  plane, for the THz magnetic field  $\mathbf{h}^\omega \parallel \mathbf{B}$  and  $\mathbf{h}^\omega \perp \mathbf{B}$ , respectively. The spectra at 10 K in zero field are taken as the respective reference. For  $\mathbf{h}^\omega \parallel \mathbf{B}$ , the lower-lying mode  $M_{1,\parallel}$  softens and becomes sharper in finite fields, together with the softening of the broad band  $M_{2,\parallel}$  [see Fig. 3(c)]. At the critical field  $B_c = 7$  T, the dynamical response is dominated by a broad continuum, extending over the whole resolvable spectra range, without any well-defined sharp excitations (the oscillations result from multiple interference at the sample surfaces). On further increasing field, the broad continuum shifts to higher energies with two new excitations splitting-off the continuum. At 9 T, the two excitations are observed at 2.7 and 4.4 meV, denoted by  $L_{1,\parallel}$  and  $L_{2,\parallel}$ , respectively, and they can be well tracked and shift to higher energies with increasing magnetic field. The two modes  $L_{1,\parallel}$  and  $L_{2,\parallel}$  are well-defined excitations, whose lineshapes become narrower on increasing fields.

The field dependence of these modes and the emergent continuum is represented in the contour plot of Fig. 3(c). The softening close to the critical field indicates that the spin gap is closed and another one is reopened, in agreement with the results obtained from other methods [26, 27, 29]. A very interesting feature of the field-induced disordered phase is the linear field dependence of the lower-lying mode  $L_{1,\parallel}$ . As shown in Fig. 3(c) this mode follows  $\hbar\omega = \hbar\omega_0 + g^*\mu_B B\Delta S$  with an apparent  $g$ -value of  $g^* = 11.1(1)$  and the Bohr magneton  $\mu_B$ , assuming a magnetic-dipole transition, i.e.  $\Delta S = 1$ . This suggests that a spin gap opens linearly with the magnetic field for the sector of the dynamical structure factor corresponding to  $\mathbf{h}^\omega \parallel \mathbf{B}$ . The linear opening of the spin gap is a feature expected for models beyond the Kitaev limit [39]. The apparent  $g^*$ -factor revealed here is significantly larger than the value of  $g_{ab} = 2.5$  estimated from the magnetization measurements [11] or  $g_{ab} = 2.27$  from the x-ray magnetic circular dichroism experiments [40], which is a reminiscence of the existence of bound states and many-body interactions in the possible QSL, as for the Heisenberg spin-1/2 chains [41, 42].

For  $\mathbf{h}^\omega \perp \mathbf{B}$  [Fig. 3(b)], approaching the critical field from below, the lower-lying mode  $M_{1,\perp}$  first slightly hardens and then softens, while the band  $M_{2,\perp}$  softens monotonically. At the critical field, the spectrum is again dom-

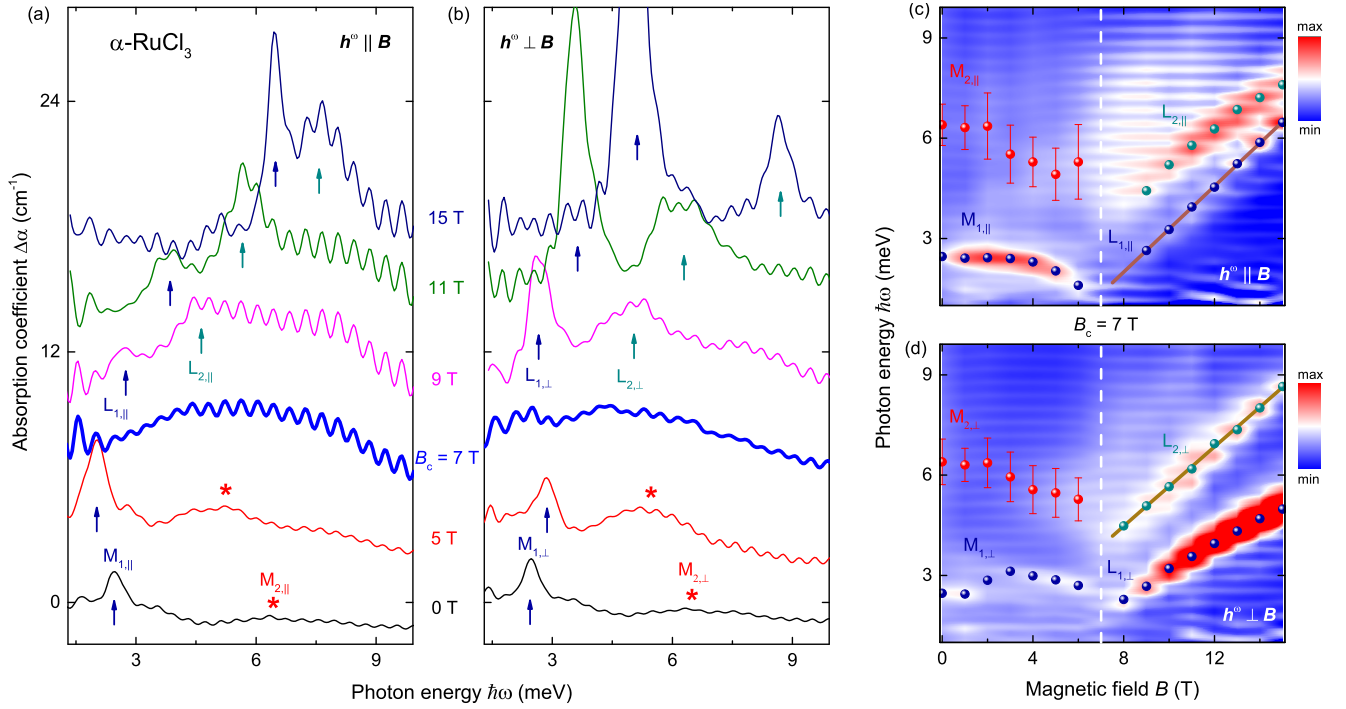


Figure 3. THz absorption spectra of  $\alpha$ -RuCl<sub>3</sub> measured at 2.4 K below and above the critical field  $B_c = 7$  T for (a) the THz magnetic field parallel ( $\mathbf{h}^\omega \parallel \mathbf{B}$ ) and (b) perpendicular to the external magnetic field ( $\mathbf{h}^\omega \perp \mathbf{B}$ ), respectively, with the spectra of 10 K taken as references. The spectra are shifted vertically by a constant for clarity. The arrows indicate the low-energy magnetic excitations with sharp absorption lines, while the asterisks mark the high-energy excitations that are rather broad. At the critical field, a broad continuum is observed which extends over the whole spectral range. Above  $B_c$ , various excitations emerge on the top of the continuum. (c)(d) Contour plot of the absorption coefficient as a function of field and photon energy for  $\mathbf{h}^\omega \parallel \mathbf{B}$  and  $\mathbf{h}^\omega \perp \mathbf{B}$ . The symbols correspond to the peak positions of the low-energy modes and the maximum positions of the high-energy bands in (a) and (b). For the broad bands, the linewidths are indicated by the error bars. Above  $B_c$ , for  $\mathbf{h}^\omega \parallel \mathbf{B}$  the lower-lying mode  $L_{1,\parallel}$  follows a linear field dependence with an apparent  $g$  value of  $g^* = 11.1(1)$  assuming a magnetic-dipole excitation [solid line in (c)], while for  $\mathbf{h}^\omega \perp \mathbf{B}$  the field dependence of the higher-lying mode  $L_{2,\perp}$  is described by the linear Zeeman term with  $g^* = 10.2(2)$  [solid line in (d)]. The vertical dashed line marks the critical field  $B_c = 7$  T.

inated by a broad continuum extending the whole spectral range. Above  $B_c$  one can identify two sharp modes  $L_{1,\perp}$  and  $L_{2,\perp}$ , both emerging on top of the continuum and shifting to higher energies together with the continuum. The absorption lines of the two modes become sharper with increasing field. In addition, the continuum is suppressed in high fields and the spectral weight is transferred to the low-lying modes. In the contour plot of Fig. 3(d) one can readily see these field-dependent features.

The emergent magnetic excitations and continuum of the field-induced quantum disordered phase exhibit clear contrast between  $\mathbf{h}^\omega \perp \mathbf{B}$  and  $\mathbf{h}^\omega \parallel \mathbf{B}$ . Both the eigenenergies and their field dependencies are different for the two polarizations, revealing the contrast of the two different sectors of dynamical structure factors. For  $\mathbf{h}^\omega \perp \mathbf{B}$  the lower-lying mode  $L_{1,\perp}$  has lower eigenenergies, and the absorption lines are much sharper and stronger than those of its counterpart  $L_{1,\parallel}$ . Moreover, the eigenenergy of  $L_{1,\perp}$  does not follow a linear field dependence, but a slower increase with the increasing field. The slower in-

crease is consistent with the results of low-temperature specific heat measurements (below 3 K) [25] where the thermodynamics is presumably dominated by the lowest-lying excitations. In contrast, the mode  $L_{2,\perp}$  in the sector of  $\mathbf{h}^\omega \perp \mathbf{B}$  can be described by the linear Zeeman term with  $g^* = 10.2(2)$ , while the  $L_{2,\parallel}$  mode hardens evidently slower than linear with the field, although these two modes have similar linewidths. These modes could be the bound states of fractionalized excitations [4–6], which are narrow and can evolve from the excitation continuum as the time-reversal symmetry is broken by the applied magnetic field [43]. It is worth noting that the continuum emerging at the quantum phase transition has been confirmed by a recent inelastic neutron scattering study [44], and the linear field dependency in the quantum disordered phase has recently also been revealed by electron spin resonance spectroscopy [45] and captured by very recent exact-diagonalization calculations [46] which predict the magnetic excitations evolving in magnetic fields above the quantum phase transition.

To conclude, terahertz spectroscopy as a function of

temperature and magnetic field reveals emergent magnetic excitations and continua in a possibly field-induced QSL in  $\alpha$ - $\text{RuCl}_3$ . While two magnonic excitations evolving on top of a continuum are resolved in the magnetically ordered phase and well below the critical field, the QSL is dynamically characterized by an emergent continuum at the quantum criticality and various magnetic excitations with distinct dependencies on field and polarization above the quantum phase transition. Our results pave the way to understand the dynamical behavior of the QSL and provide constraints for a quantitative theoretical description, e.g. via the identification of a realistic model or by extending the Kitaev model with terms breaking the time-reversal symmetry.

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