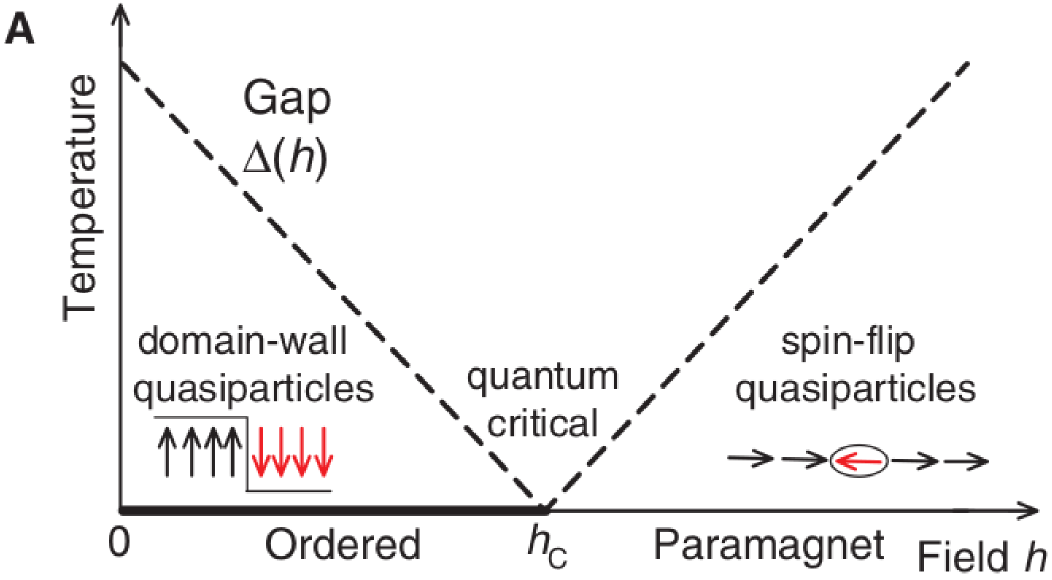
Quantum spin dynamics of quasi-one-dimensional Heisenberg-Ising magnets in a transverse field: confined spinons, E_8 spectrum, and quantum phase transitions

Kirill Amelin[1,*], Johan Viirok[1], Urmas Nagel[1], Toomas Rõõm[1], Johannes Engelmayer[2], Tusharkanti Dey[2,3], Agustinus Agung Nugroho[2,4], Thomas Lorenz[2] and Zhe Wang[5,*]

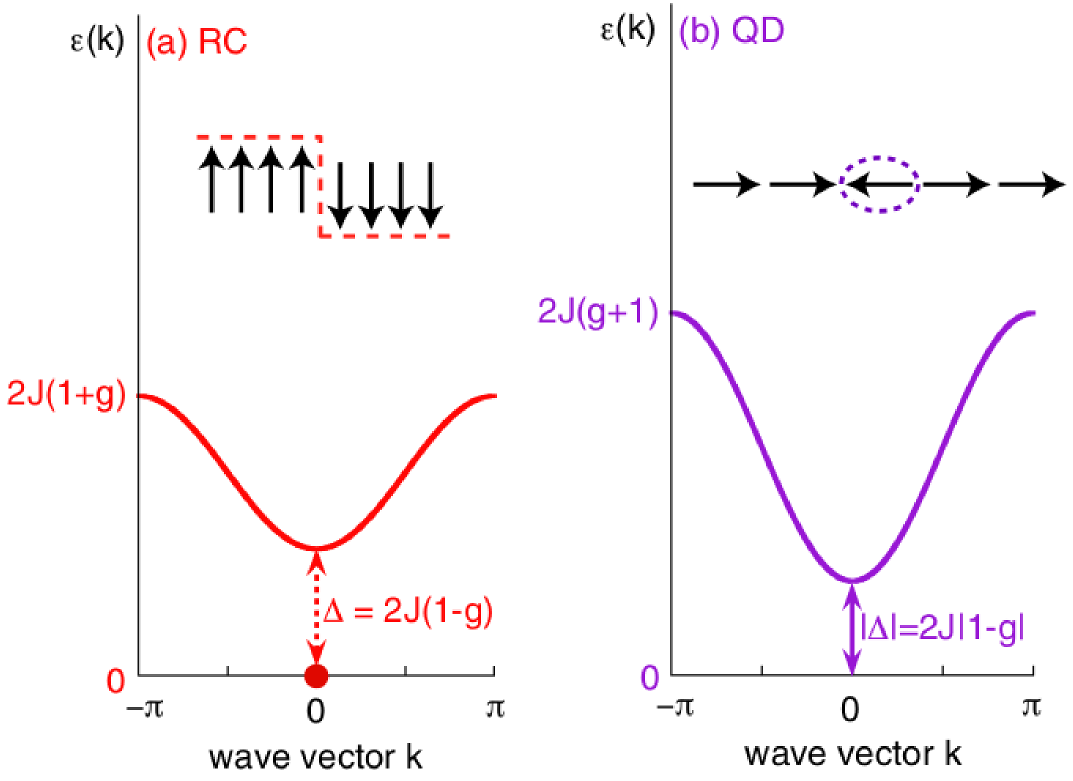
[1] National Institute of Chemical Physics and Biophysics, 12618 Tallinn, Estonia
[2] Institute of Physics II, University of Cologne, 50937 Cologne, Germany
[3] Department of Physics, Indian Institute of Technology (Indian School of Mines), Dhanbad 826004, Jharkhand, India
[4] Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, 40132 Bandung, Indonesia
[5] Department of Physics, TU Dortmund University, 44227 Dortmund, Germany

1D Transverse-field Ising model

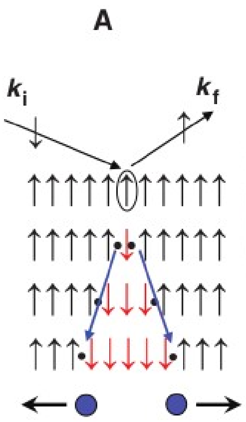
$$H = \Sigma_i - JS_i^z S_{i+1}^z - hS_i^x$$



1D Ising model



1D Ising model: INS



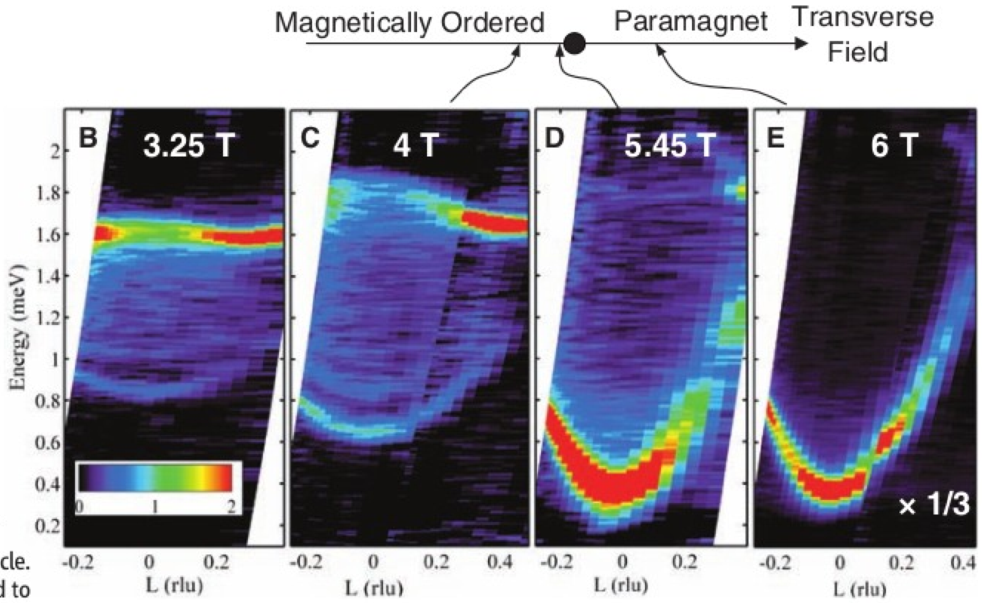


Fig. 2. (**A**) Cartoon of a neutron spin-flip scattering that creates a pair of independently propagating kinks in a ferromagnetically ordered chain. (**B** to **E**) Spin excitations in $CoNb_2O_6$ near the critical field as a function of wave vector along the chain (in rlu units of $2\pi/c$) and energy (*18*). In the ordered phase [(B) and (C)], excitations form a continuum due to scattering by pairs of kinks [as illustrated in (A)]; in the paramagnetic phase (E), a single dominant sharp mode occurs, due to scattering by a spin-flip quasiparticle. Near the critical field (D), the two types of spectra tend to merge into one another. Intensities in (E) are multiplied by 1/3 to make them comparable to the other panels.

Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E_8 Symmetry

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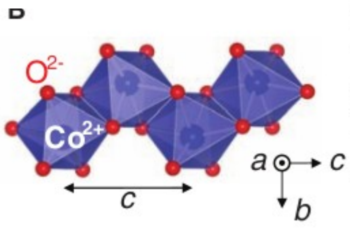
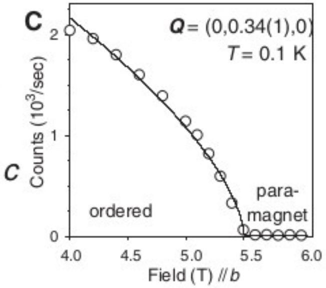
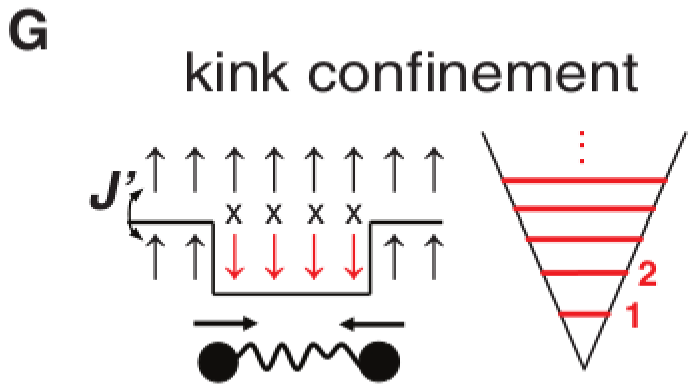




Interchain coupling or longitudinal field



$$h_z = \Sigma_\delta J_\delta \langle \mathbf{S}^z \rangle$$

$$\lambda = 2h_z \langle \mathbf{S}^z \rangle / \tilde{\mathbf{c}},$$

$$V(x) = \lambda |x|,$$

$$-\frac{\hbar^2}{\mu}\frac{d^2\varphi}{dx^2} + \lambda|x|\varphi = (E - 2E_0)\varphi$$

Kink confinement

$$-\frac{\hbar^2}{\mu}\frac{d^2\varphi}{dx^2} + \lambda|x|\varphi = (E - 2E_0)\varphi$$

$$E_i = 2E_0 + \zeta_i \lambda^{2/3} \left(\frac{\hbar^2}{\mu}\right)^{1/3}, \qquad i = 1, 2, 3, \ldots,$$

$$\mathrm{Ai}(-\zeta_i) = 0$$ - Airy function

THz Spectroscopy

$$\alpha \equiv \Delta\alpha(B) = \alpha(B, 2.7\,\mathrm{K}) - \alpha(0\,\mathrm{T}, 10\,\mathrm{K}) = -\frac{1}{d}\ln\left[\frac{I(B, 2.7\,\mathrm{K})}{I(0\,\mathrm{T}, 10\,\mathrm{K})}\right], \qquad (5)$$

where $I(B,T)$ is the transmitted intensity in a given field B at a given temperature T, and d denotes the sample thickness. For this insulator with relatively weak absorption peaks of

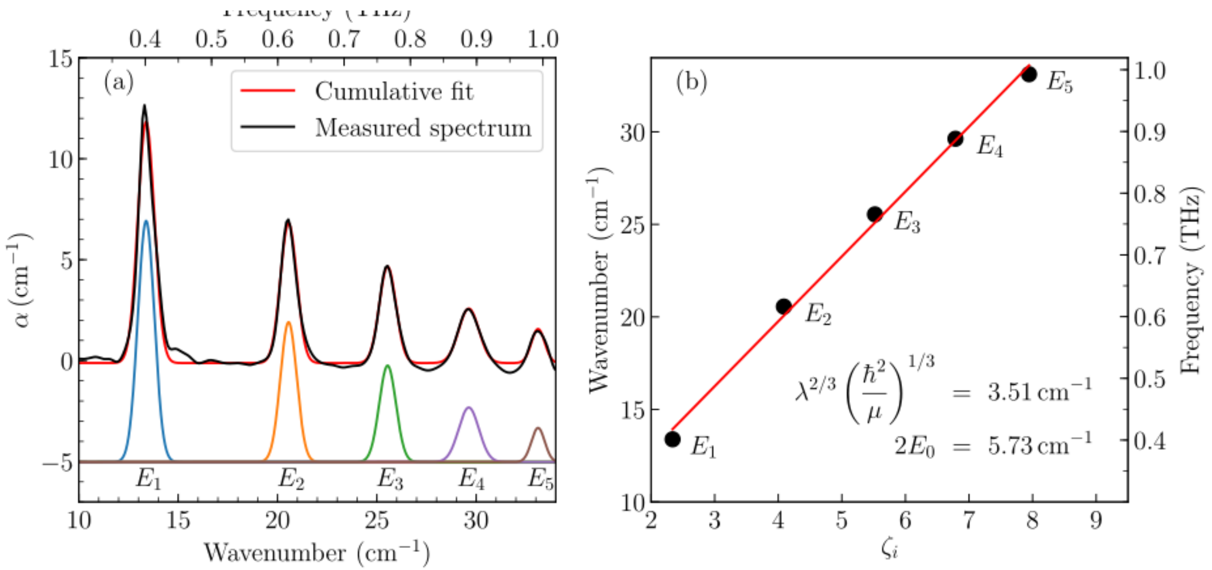


Figure 5. (a) Zero-field spectrum of $BaCo_2V_2O_8$ at 2.7 K below T_N. Fits of the five absorption peaks E_1–E_5 are shown under the spectrum. The red line shows the cumulat-

THz Spectroscopy

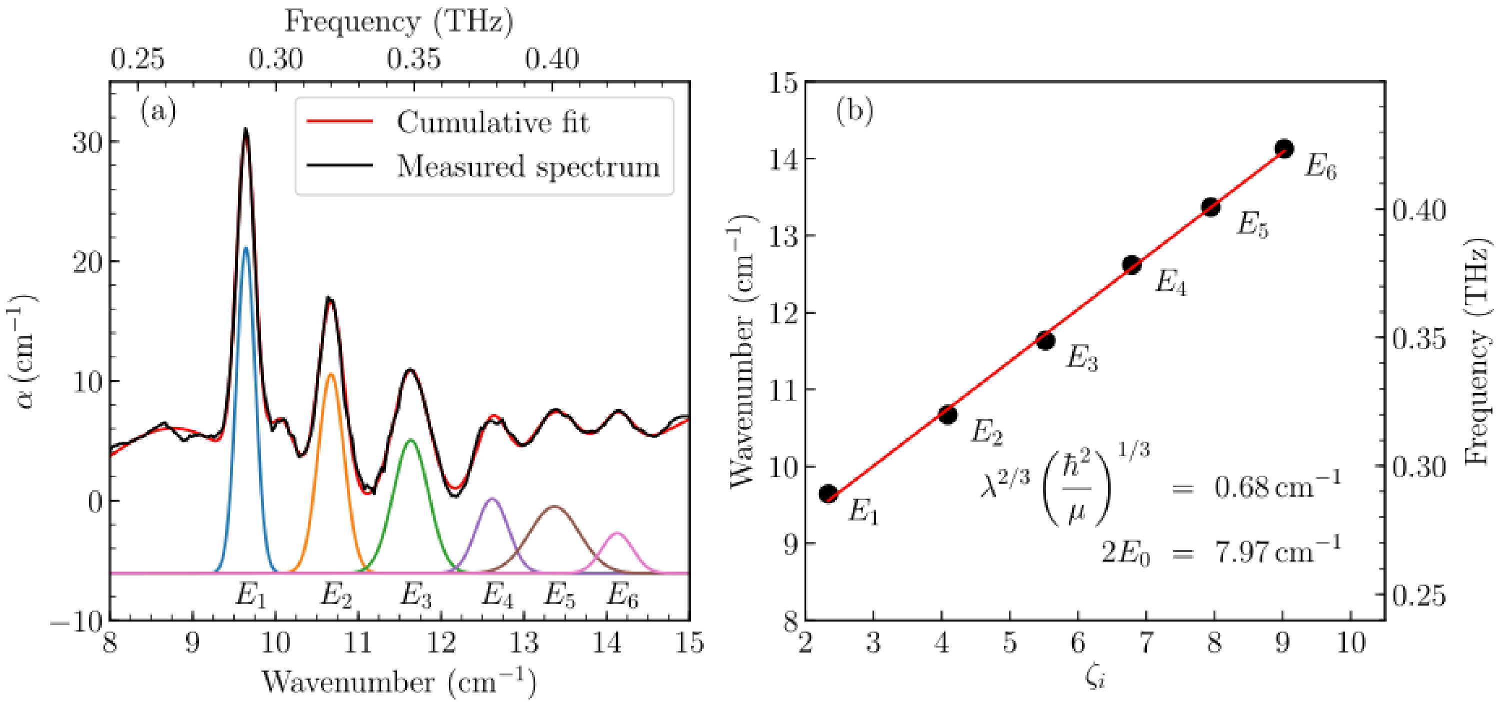
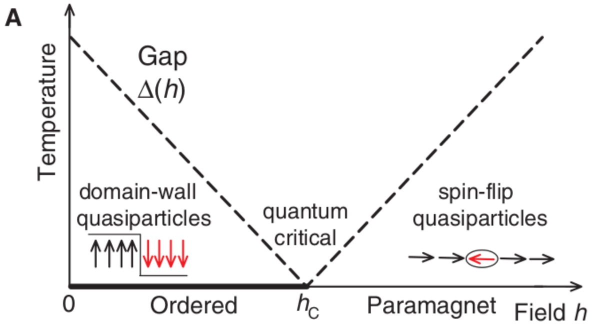


Figure 6. (a) Zero-field spectrum of $CoNb_2O_6$ at 250 mK below T_C. Fits of the six absorption peaks E_1–E_6 are shown under the spectrum. The red line shows the cumulative absorption, which includes the six peaks and a wide absorption background. (b) Absorption peak energies follow a linear dependence on ζ_i, the negative zeros of the Airy function $A_i(-\zeta_i) = 0$, for $2E_0 = 7.97\,\mathrm{cm}^{-1}$ and $\lambda^{2/3}(\frac{\hbar^2}{\mu})^{1/3} = 0.68\,\mathrm{cm}^{-1}$.

Critical point



$$H_{1/2}^{(1,2)} = H_{1/2} + h \int \sigma(x)\, d^2x$$

INTEGRALS OF MOTION AND S-MATRIX OF THE (SCALED) $T = T_c$ ISING MODEL WITH MAGNETIC FIELD

A. B. ZAMOLODCHIKOV*

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, England.

Received 24 January 1989

Exactly solvable

$$H^{(1,2)}_{1/2} = H_{1/2} + h \int \sigma(x) d^2x$$

$$m_1 = m; \qquad m_2 = 2m\cos\frac{\pi}{5}; \qquad m_3 = 2m\cos\frac{\pi}{30};$$

$$m_4 = 2m_2\cos\frac{7\pi}{30}; \qquad m_5 = 2m_2\cos\frac{2\pi}{15}; \qquad m_6 = 2m_2\cos\frac{\pi}{30};$$

$$m_7 = 4m_2\cos\frac{\pi}{5}\cos\frac{7\pi}{30}; \qquad m_8 = 4m_2\cos\frac{\pi}{5}\cos\frac{2\pi}{15}.$$

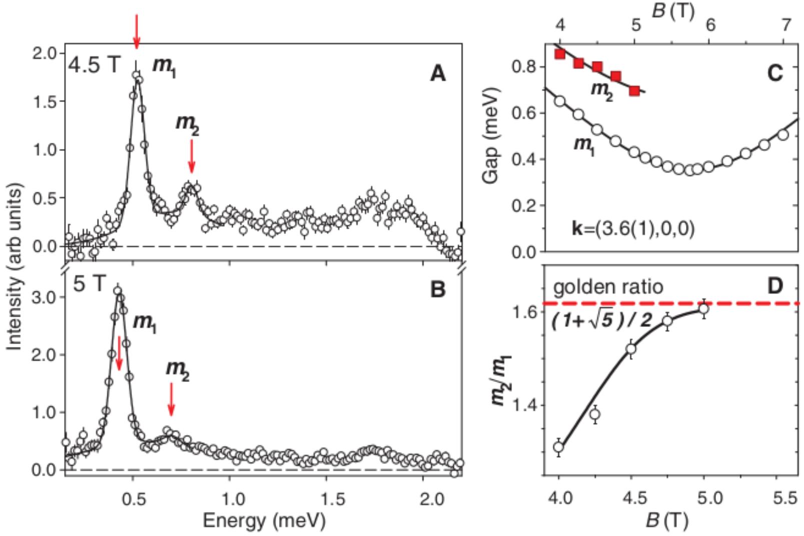
$$\frac{m_2}{m_1} = \frac{\sqrt{5}+1}{2}$$

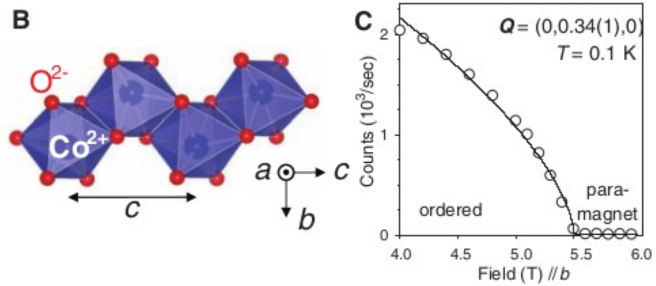
The exact relations between the coupling constants and the masses of particles for the integrable perturbed Conformal Field Theories

V.A. Fateev [1]
Laboratoire de Physique Mathématique [2], Montpellier, France [3]

Received 29 September 1993
Editor: R. Gatto

E8 Golden ratio in INS





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E8 excitations

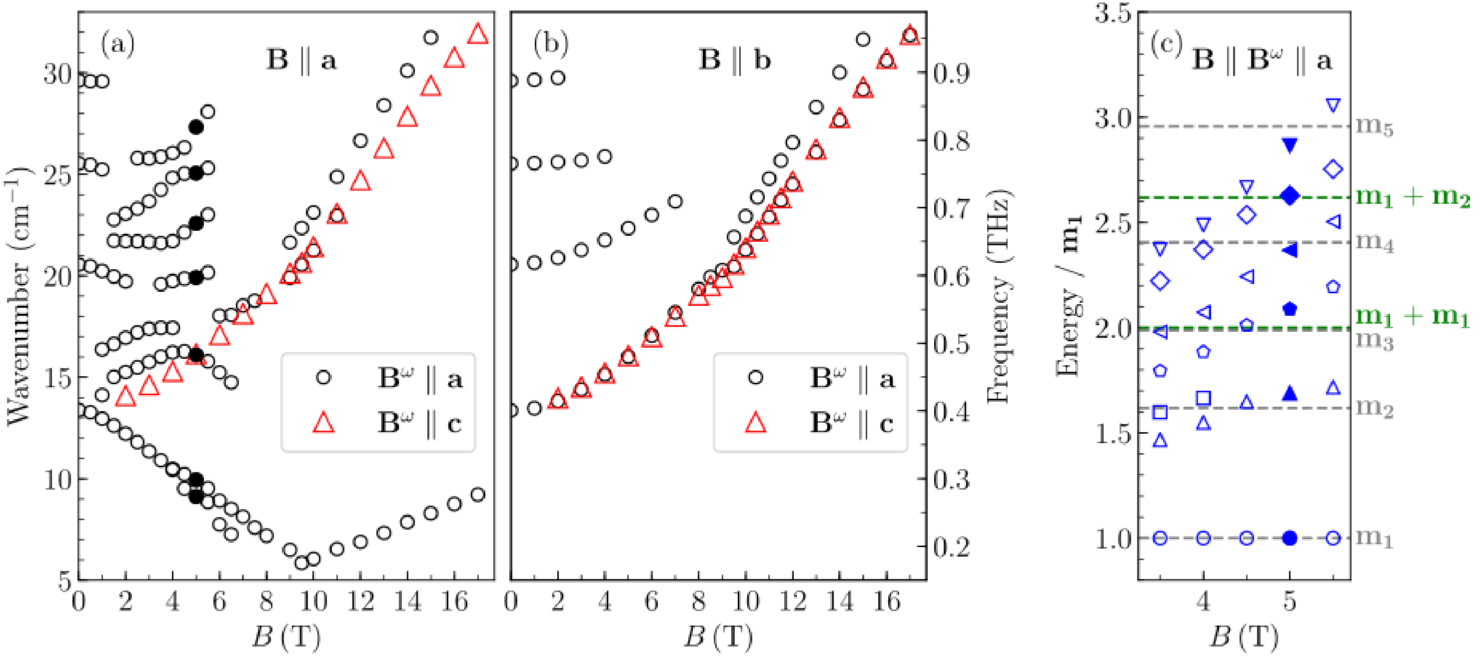

Figure 8. $BaCo_2V_2O_8$ absorption peak frequency dependence on the magnetic field at 2.7 K for the two field directions: (a) **B** ∥ **a** and (b) **B** ∥ **b**. Solid black dots in (a) indicate the E_8 excitations at $B_{\perp}^{c,1D}$. (c) Ratios of the excitation energies with respect to the lowest-frequency excitation m_1 for the field direction **B** ∥ **a** close to $B_{\perp}^{c,1D}$. The ratios approach theoretically predicted values for the E_8 excitations (marked with dashed lines) at 5 T.

E8 excitations

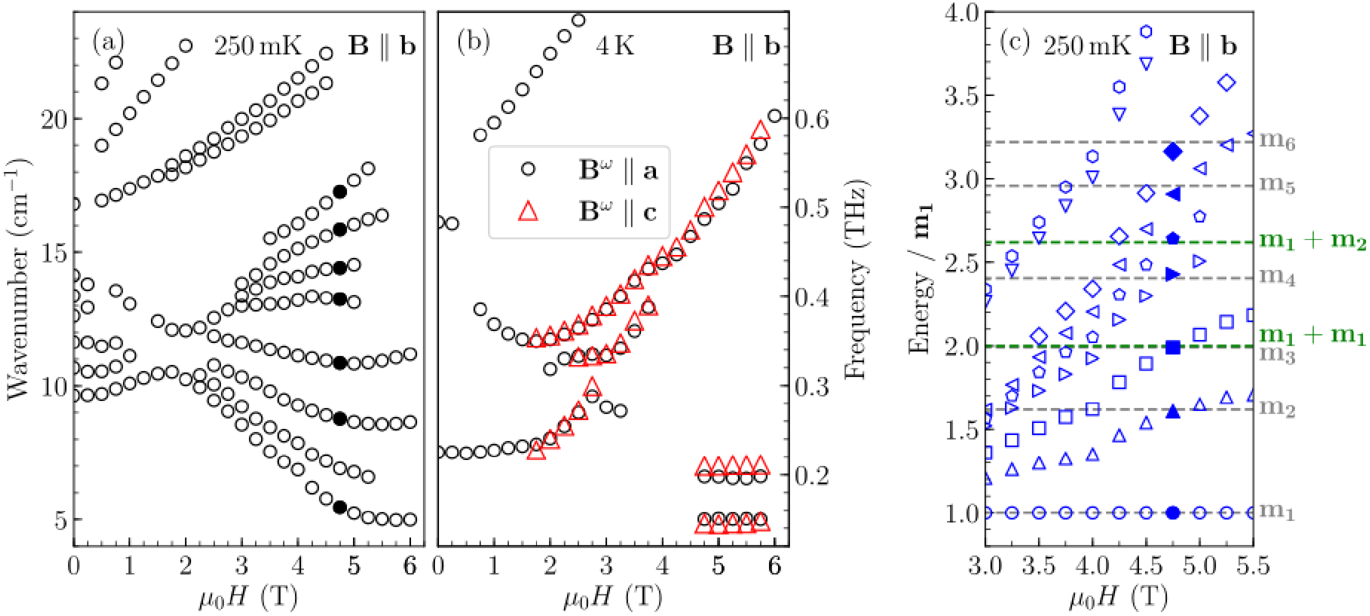

Figure 9. (a) $CoNb_2O_6$ absorption peak frequency dependence on the magnetic field $\mathbf{B} \parallel \mathbf{b}$ at 250 mK (see figure 4). Solid markers indicate the E_8 excitations at $B_{\perp}^{c,1D}$. (b) Resonance frequency as a function of the applied magnetic field at 4 K, which is above T_C. (c) Ratios of the excitation energies with respect to the lowest-frequency excitation m_1 for the field direction $\mathbf{B} \parallel \mathbf{b}$ close to $B_{\perp}^{c,1D}$ (see black dots in (a)). The ratios approach theoretically predicted values for the E_8 excitations (marked with dashed lines) at 4.75 T.