Anisotropy-induced soliton excitation in magnetized strong-rung spin ladders.

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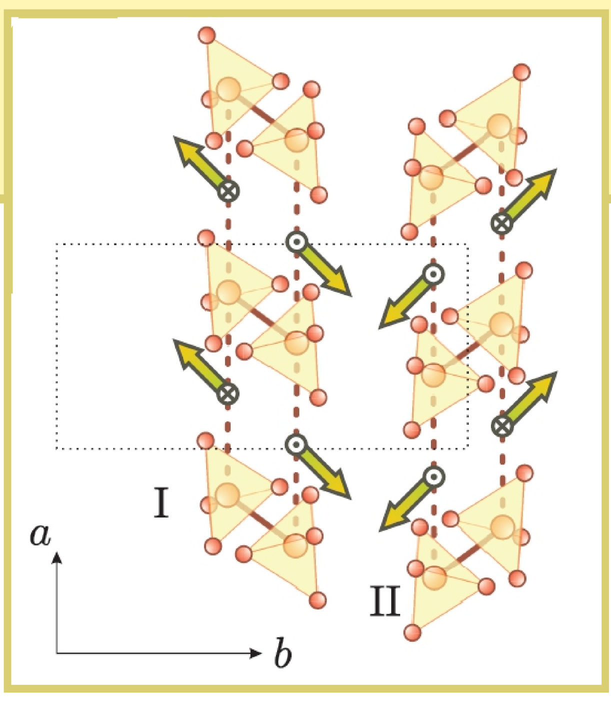
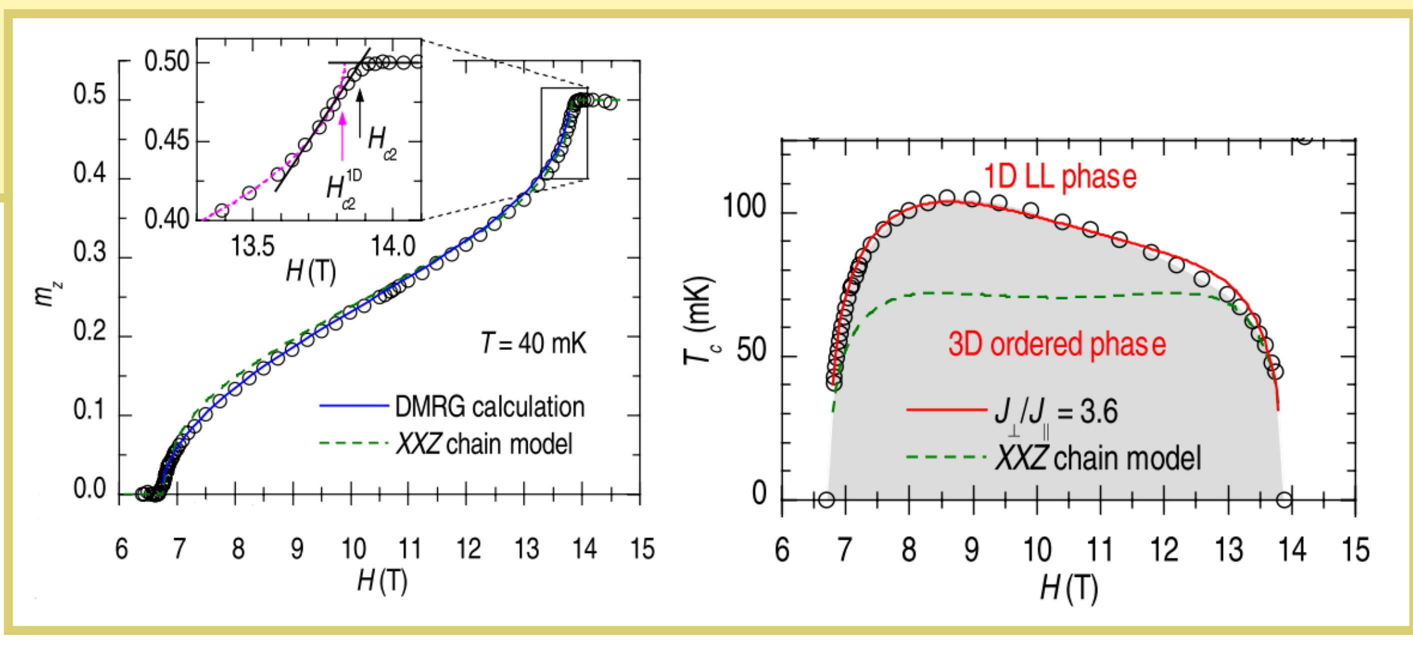
Introduction: Strong-rung spin ladder magnet BPCB

Compound $(C_5H_{12}N)_2CuBr_4$ (BPCB for short) is a spin-ladder model material with dominating exchange coupling on the rungs of the ladder structure. The rung exchange coupling constant J_{rung}=12.7 K and the leg coupling constant J_{leg}=3.54 K [Phys. Rev. B **83** (2011), 054407]. The excitation spectrum of BPCB features an energy gap Δ=9.2K, the low-temperature magnetization curve demonstrates two critical fields H_{c1}=66kOe and H_{c2}=136kOe. Field induced antiferromagnetic ordering is observed below 100 mK [Phys. Status Solidi C 247 (2010), 656].
BPCB crystal symmetry (monoclinic C^5_{2h}) allows for a Dzyaloshinskii-Moriya interaction with a particular pattern: DMI is forbidden on the rung of the ladder structure, DMI is uniform along the legs of the ladder structure, and DM vectors on the legs of the ladder are exactly opposite.

BPCB sample image, from https://neutron.ethz.ch/quantum-materials/bpcb.html

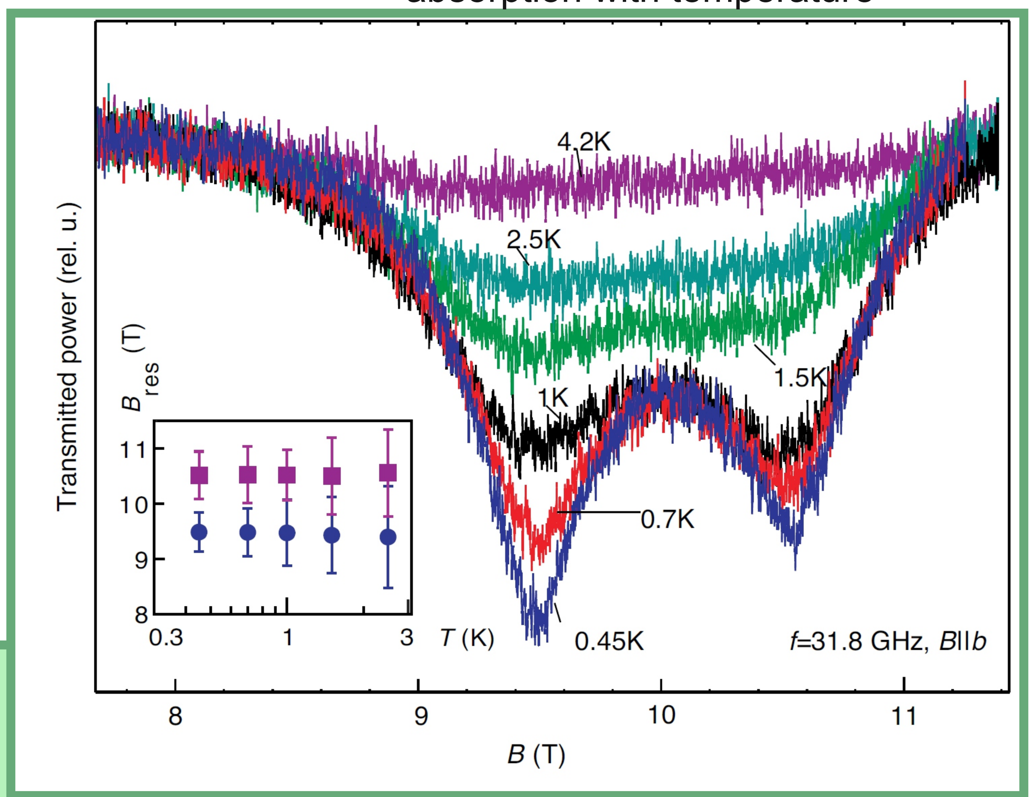


Scheme of the BPCB crystal structure(C^5_{2h}), arrows show directions of DM vector



Low temperature magnetization curve for BPCB (left) and low temperature phase diagram (right) [Phys. Status Solidi C 247 (2010), 656].

Evolution of the high-field ESR absorption with temperature

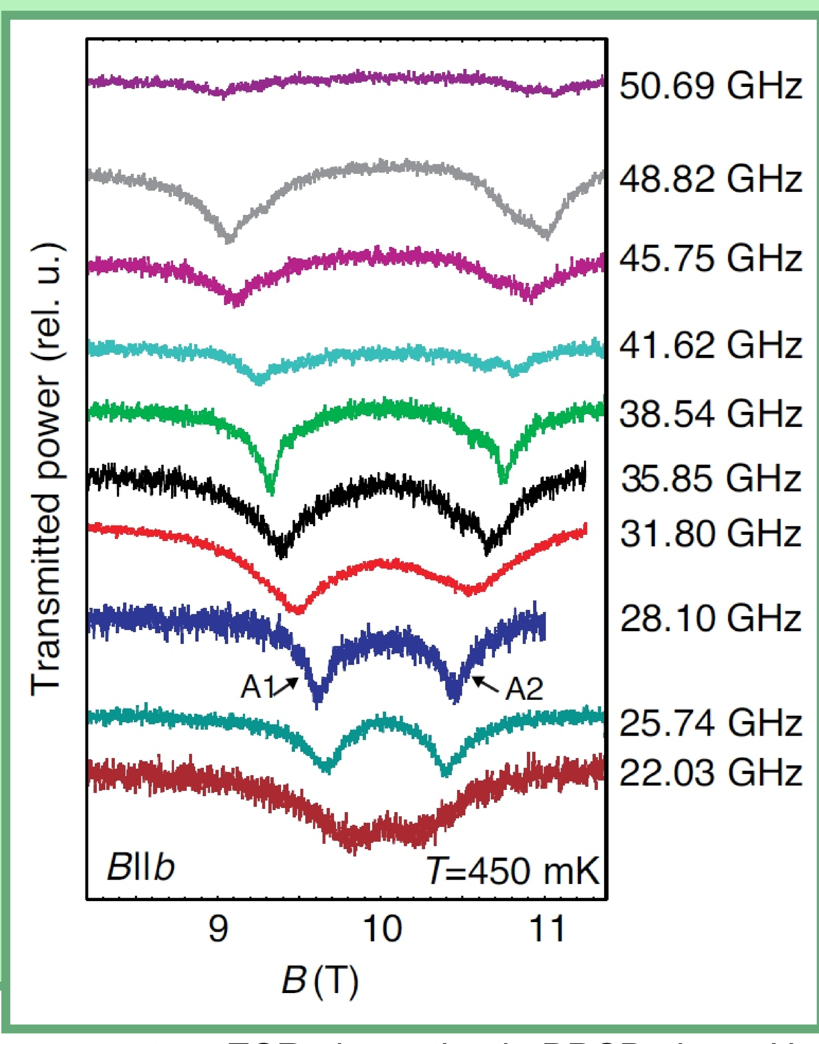


Experiment: ESR spectroscopy above H_{c1}

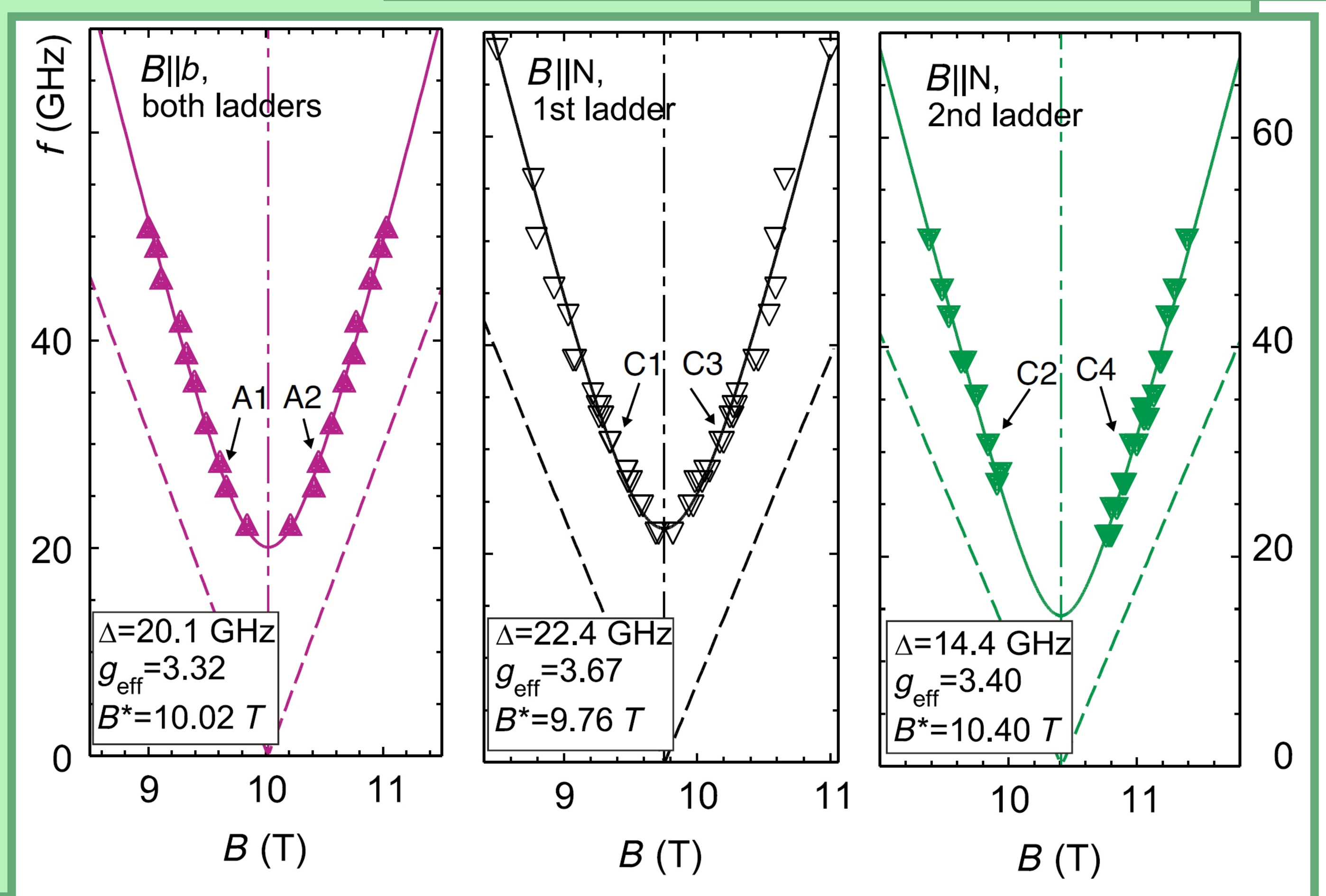
Experimental details: 20...100 GHz, 0...12 T, 0.45...10 K

Main results:

- observation of low frequency ESR mode above H_{c1}
- this mode demonstrates anisotropic frequency-field dependence with minimum close to $(H_{c1}+H_{c2})/2$ and asymptotic slope corresponding to g=3.3...3.6
- this mode is observed well above the ordering temperature (~100 mK), it vanishes on heating up to ~3 K



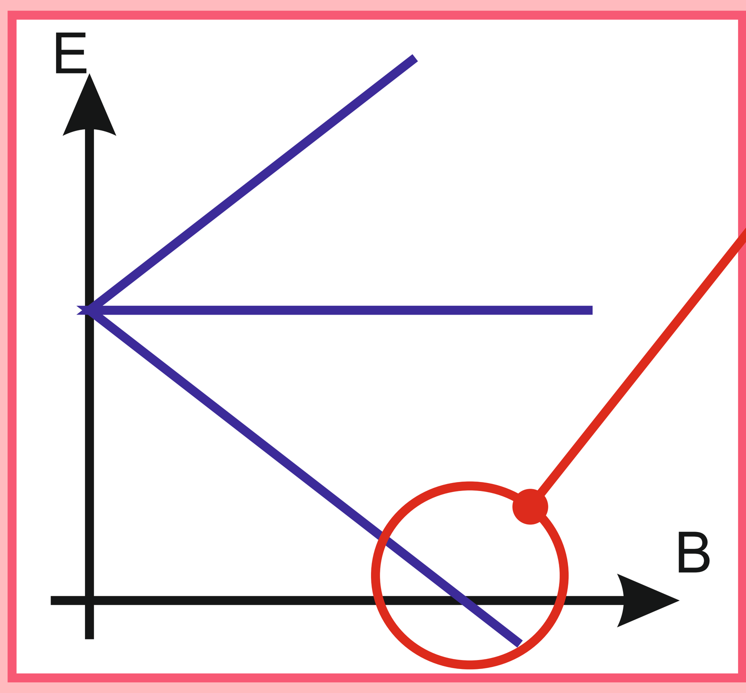
Low temperature ESR absorption in BPCB above H_{c1}



Frequency-field diagrams for the observed high-field ESR mode. B||N denotes field applied along bisector of (bc) plane - ESR signals from two types of ladder structures are resolved in this case due to g-factor anisotropy

Theory: Mapping of the spin ladder on XXZ chain model, DMI, ESR and solitonic excitations

(for details see Phys.Rev.Lett 125, 027204 (2020) and Supplementary material there)



(i) In the limit of weakly coupled dimers ("extremely strong runged" ladder) at $H \cong \Delta/(g\mu_B)$ only two lowest levels matter allowing for T=1/2 pseudospin description of the spin ladder.
(ii) Pseudospin mapping transform Heisenberg spin ladder to XXZ pseudospin chain in an effective field [e.g., Phys.Rev. B 83, 054407 (2011)]

$$\hat{\mathcal{H}}_{XXZ} = \sum_j J_\parallel \left(\hat{T}^x_j \hat{T}^x_{j+1} + \hat{T}^y_j \hat{T}^y_{j+1} + \frac{1}{2}\hat{T}^z_j \hat{T}^z_{j+1}\right) - g\mu_B \left(B - \frac{J_\perp + J_\parallel/2}{g\mu_B}\right)\hat{T}^z_j$$

(iii) Symmetry allowed DMI transforms to uniform DM interaction in XXZ pseudospin model

$$\hat{\mathcal{H}}'_{XXZ} = \frac{D_x}{\sqrt{2}}\sum_j (\hat{T}^y_j \hat{T}^z_{i+1} - \hat{T}^z_j \hat{T}^y_{j+1})$$

(iv) 1D Tomonaga-Luttinger liquid theory taking into account uniform DMI yields solitonic solutions which turns to be ESR active, while "normal" excitations of pseudospin XXZ chain are ESR-silent. The observed ESR gap (soliton "mass") is determined by DM vector component transverse to the field, while the effective g-factor value is determined in a parameter-free way:

$$g_{\text{eff}} = 2Kg$$

here K is Tomonaga-Luttinger liquid parameter, it is determined by exchange coupling parameters of the spin ladder. For BPCB K=0.8 in a nice agreement with the experiment.

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