Band Structure of Helimagnons in MnSi Resolved by Inelastic Neutron Scattering

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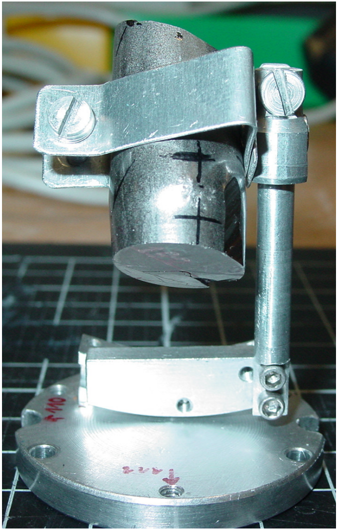
3. DMI Workshop: 26-30 May 2015 Pskov, Russia

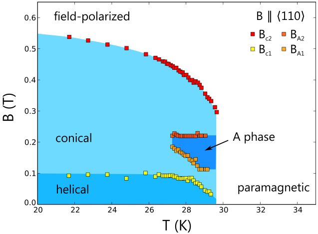
Outline

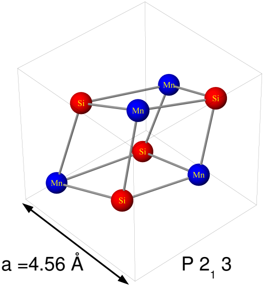
- summary of the helimagnon model
- introduction to the instrument MIRA
- specific setups and example scans
- result: helimagnon dispersion relation



Basics on MnSi

S. Mühlbauer et al., Science 323 915 (2009).





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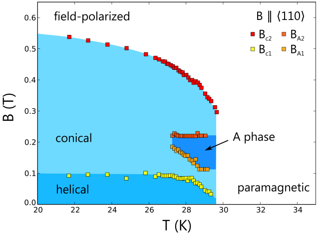

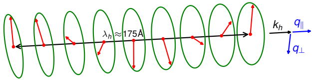

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  - exchange interaction $\Rightarrow$ parallel spins
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  - together $\Rightarrow$ long spin spiral: $\sim$180 Å

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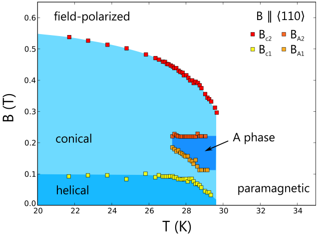

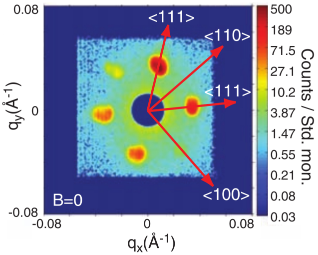

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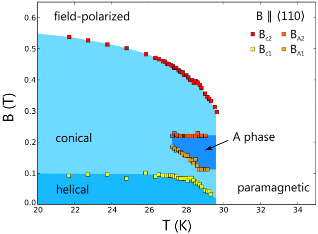

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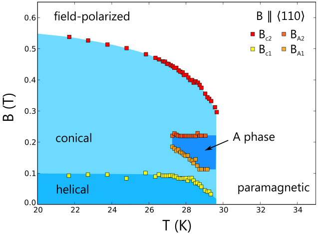

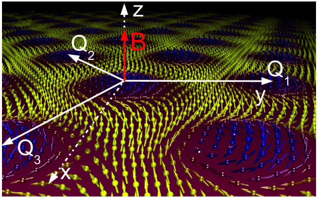

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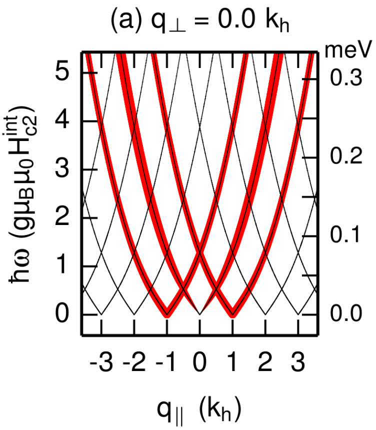
- skyrmion phase: three phase-coherent helices in an equilateral triangle: $\sim$0.2 T



model parameters (MnSi, 20 K):

1. momentum scale:
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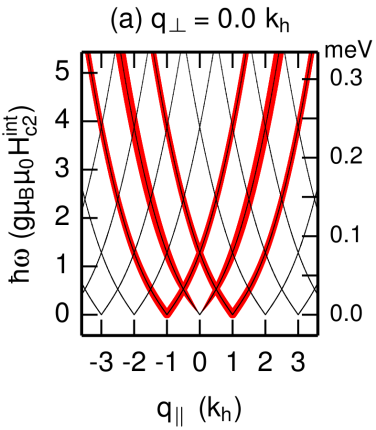
Helimagnons in Single-Domain State



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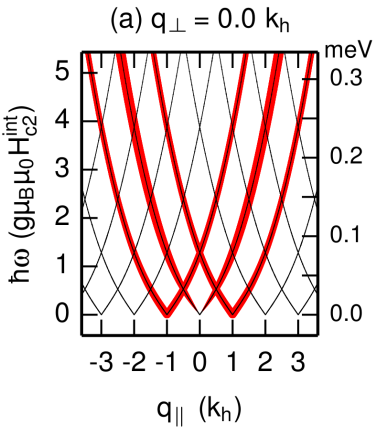

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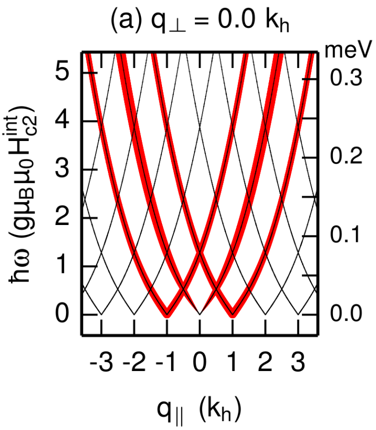

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parameters are well known

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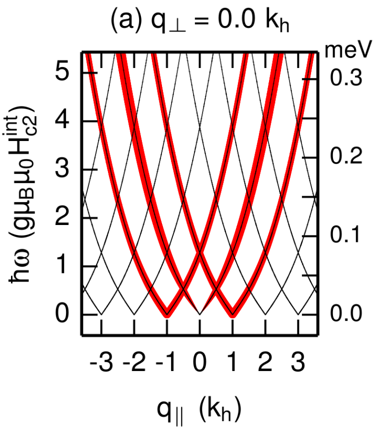

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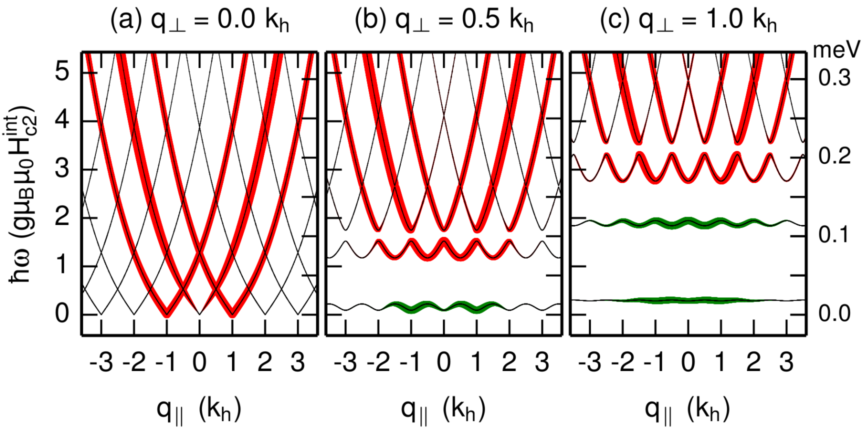

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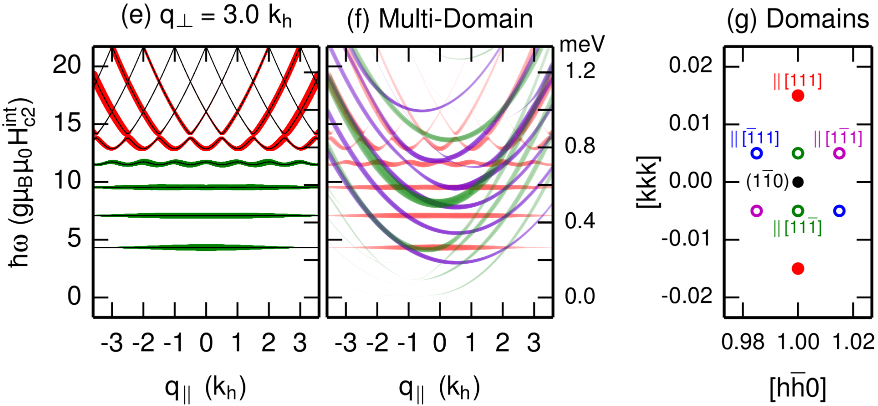
$q_\perp > 0$: number, energies and 'flatness' of bands increase with $q_\perp$

Multi-Domain vs. Single-Domain

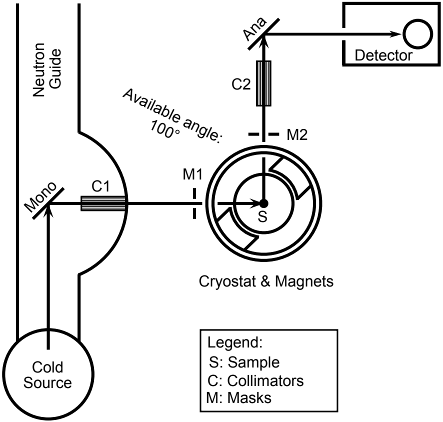


- momentum notation: with respect to the red domain || [111]
- zero field: contributions from four domains ⇒ intensity plateaus
- small field: single-domain state ⇒ well defined peaks

multi-domain measurements: Janoschek et al., PRB **81** 214436 (2010).

Triple-Axis Spectrometer (TAS)

- neutron guide $\Rightarrow$ white beam



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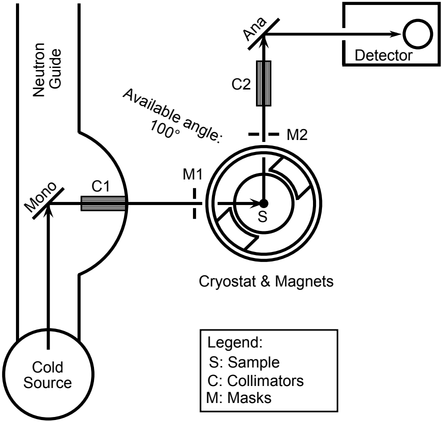
  1. monochromator angle:
     selects initial energy E_i



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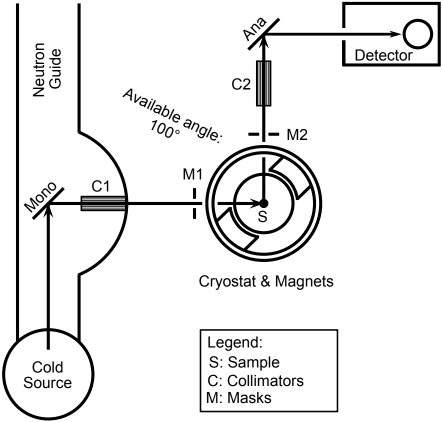

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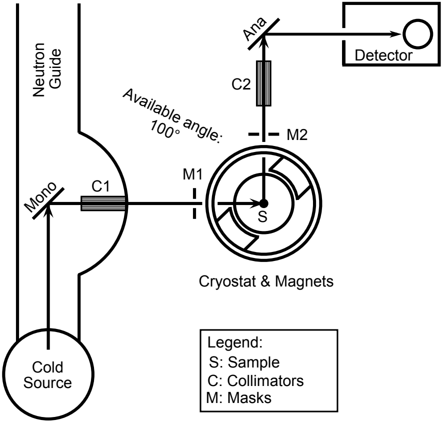
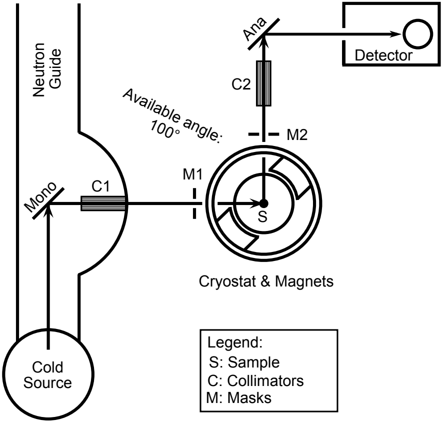


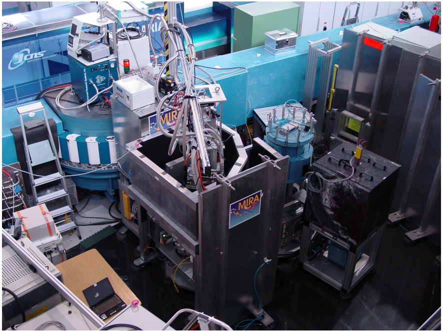
Triple-Axis Spectrometer (TAS)

- neutron guide $\Rightarrow$ white beam
- three rotation axes:
  1. monochromator angle:
     selects initial energy E_i
  2. scattering angle at sample:
     selects $\mathbf{Q} = \mathbf{G} + \mathbf{q}$
  3. analyzer angle:
     selects final energy E_f
- energy transfer $\hbar\omega = E_i - E_f$:
  - magnon creation: $\hbar\omega > 0$
  - mag. annihilation: $\hbar\omega < 0$
- find dispersion relation $\hbar\omega(\mathbf{q})$



The Cold TAS MIRA@FRM-II

- location: guide hall of FRM-II
- cold neutrons: E_i = 3...5 meV
- multi-purpose instrument:
  - SANS $\Rightarrow$ structure
  - TAS $\Rightarrow$ dynamics
- two samples $\sim$8 cm^3, $\eta \approx 10'$
- mostly at 20 K ($\sim {}^2\!/_3 T_C$)
- E_i and **q** constant $\Rightarrow$ scan $\hbar\omega$



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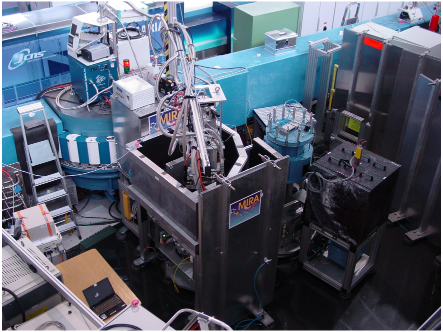
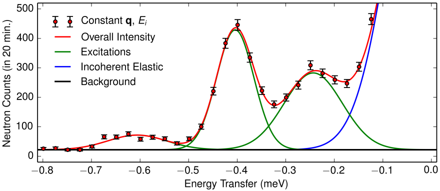
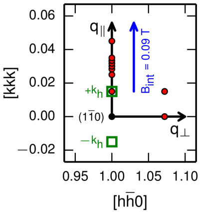
- generic example scan $\longrightarrow$





Setup 1: Dispersive Branches

- horizontal B $\Rightarrow$ $\mathbf{k}_h$ in plane
- can select both: $q_{||}$ & $q_{\perp}$
- suboptimal for the bands,
  but can show: they're flat



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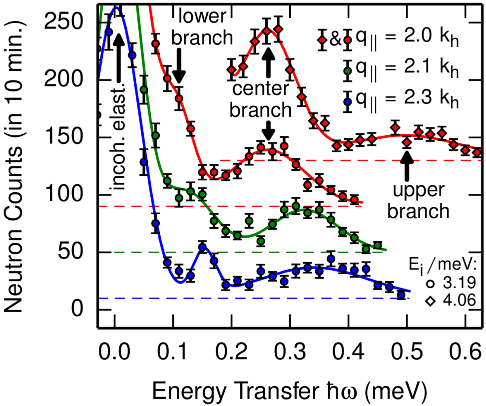
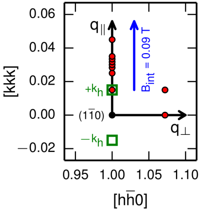
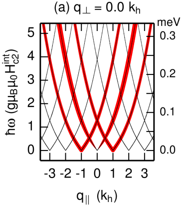
- can select both: $q_{\parallel}$ & $q_{\perp}$
- suboptimal for the bands, but can show: they're flat
- ideal for the 3 dispersive branches at $q_{\perp} = 0$ $\longrightarrow$



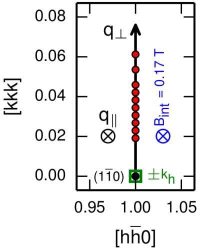




(example scans at 20 K)

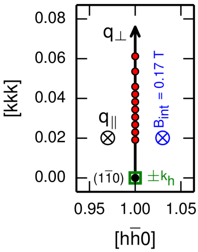
Setup 2: Helimagnon Bands

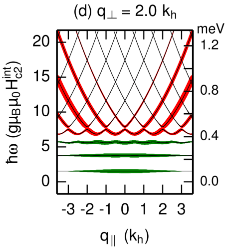
- vertical field $\Rightarrow$ $\mathbf{k}_h \perp$ plane
- tune band energies with $q_\perp$
- course vertical resolution ($q_{||}$)
  $\Rightarrow$ collect large band intensity

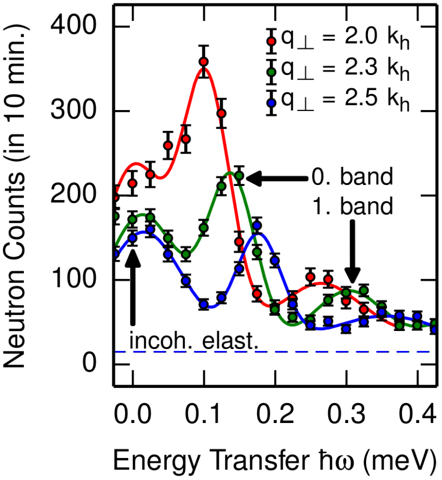


Setup 2: Helimagnon Bands

- vertical field ⇒ $\mathbf{k}_h \perp$ plane
- tune band energies with $q_\perp$
- course vertical resolution ($q_{||}$)
  ⇒ collect large band intensity
- resolve the first two bands →



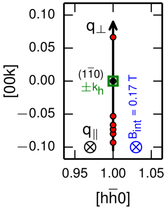




($T = 20$ K, $E_i = 4.06$ meV)

Setup 3: Even More Bands

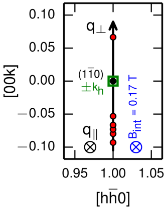
- another orientation: $q_\perp \,||\, [111] \rightarrow q_\perp \,||\, [001]$
  $\Rightarrow$ same result, decoupled from nuc. lattice

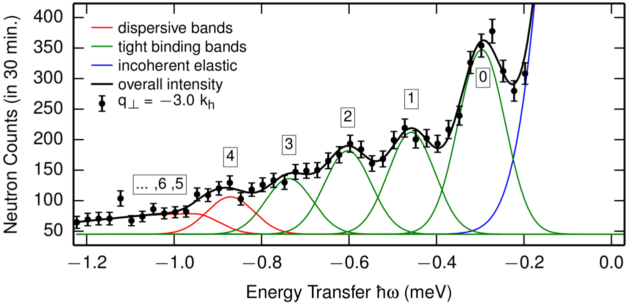


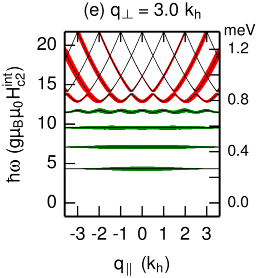
Setup 3: Even More Bands

- another orientation: $q_\perp \parallel [111] \rightarrow q_\perp \parallel [001]$
  $\Rightarrow$ same result, decoupled from nuc. lattice

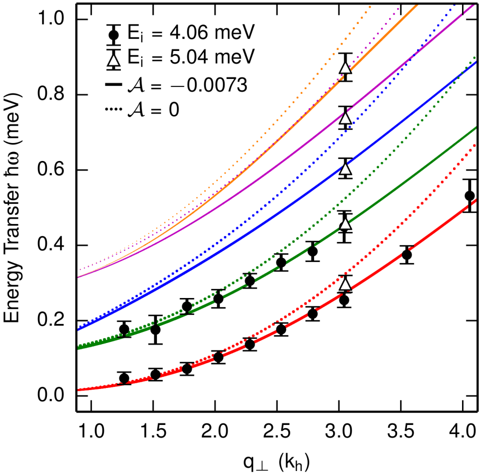
- $\hbar\omega < 0$: increases efficiency $\Rightarrow$ more bands
  E-dependent analyzer efficiency overcomes Bose statistics.







Results for the Helimagnon Bands



- band energies vs. $q_\perp$ at 20 K, setups 2 & 3
- dotted lines:
  -universal spectrum
  -agrees at low $\hbar\omega$ ✓
  -deviates at large $\hbar\omega$

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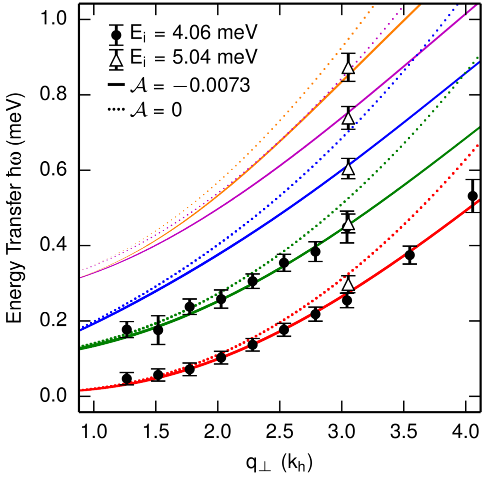
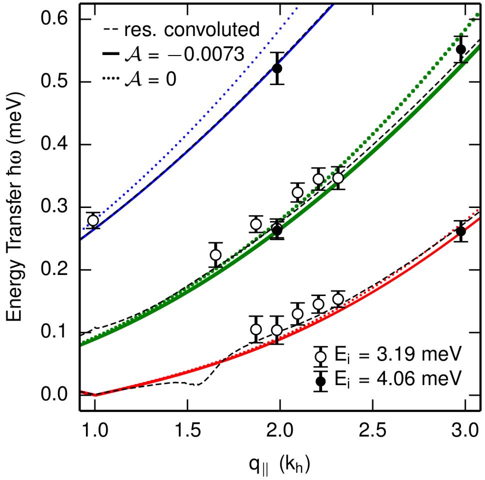


- band energies vs. $q_\perp$ at 20 K, setups 2 & 3
- dotted lines:
  -universal spectrum
  -agrees at low $\hbar\omega$ ✓
  -deviates at large $\hbar\omega$
- full lines:
  -higher order correction
  -agreement for all $\hbar\omega$ ✓
  -$\mathcal{A} \sim (ak_h)^2 \approx 0.01$ ✓
  -at $3k_h \to 3^2(ak_h)^2 \sim 10\%$

$$\mathcal{F} \sim (\nabla_i \hat{n}_j)^2 + 2k_h \hat{n}(\nabla \times \hat{n}) + \frac{\mathcal{A}}{k_h^2}(\nabla^2 \hat{n})^2 \text{ + dipolar + Zeeman}$$

Results for the Dispersive Branches



- dispersive modes vs. $q_{\parallel}$ at 20 K, setup 1
- higher order correction:
  -important for blue branch
  -not for the red/green one

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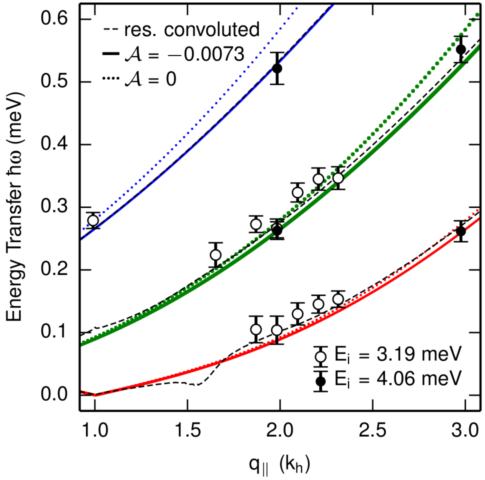
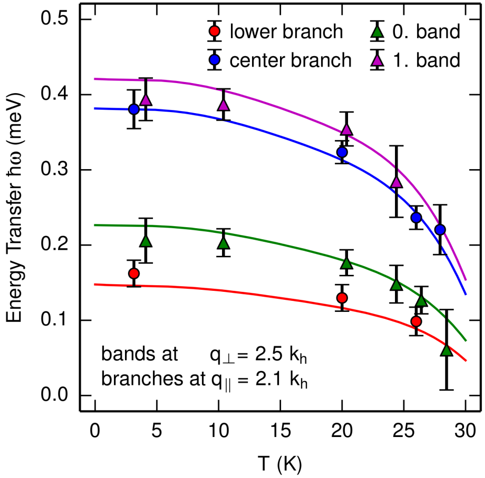


- dispersive modes vs. $q_{\parallel}$ at 20 K, setup 1
- higher order correction:
  -important for blue branch
  -not for the red/green one
- black dashed lines:
  -vertical resolution $\pm\, ^1/_2\, k_h$
  -along $q_{\perp} \Rightarrow$ band split-off
  -10% effect for red branch
  -small effect for the others
- resolve all three modes ✓

Renormalization of the Helimagnons



- until now: $\hbar\omega(\mathbf{q}, T = 20\,\mathrm{K})$
- next: $\hbar\omega(\mathbf{q} = \mathrm{constant}, T)$:
  -setup 1: $q_{\|} = 2.1\,k_h$
  -setup 2: $q_{\perp} = 2.5\,k_h$
- two modes for each setup

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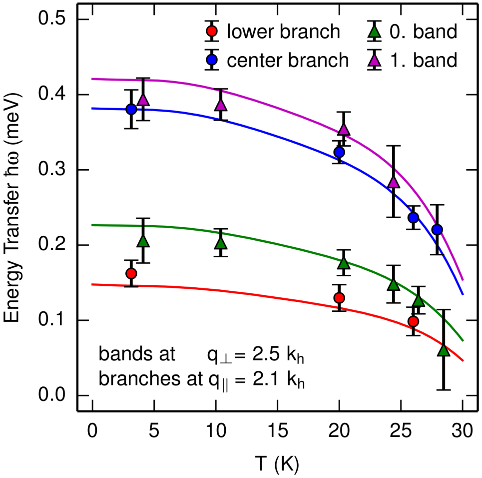

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- two modes for each setup
- full lines include:
  -mainly $H_{c2}^{\text{int}}(T) \leftarrow \chi_{\text{ac}}$ [1]
  -$k_h(T) \leftarrow$ SANS [2] & TAS
  -resolution convolution

[1] Bauer *et al.*, PRB **82**, 064404 (2010).
[2] Grigoriev *et al.*, PRB **74**, 214414 (2006).

Conclusion

- summary:
  - clear identification due to the single-domain state
  - all three dispersive branches and at least five bands
  - softening of the helimagnons like $H_{c2}(T)$ along $q_{||}$ & $q_{\perp}$
  - parameter-free prediction confirmed for low energies
  - single parameter $\mathcal{A} = -0.0073 \pm 0.0004$ for all energies
- outlook:
  - helimagnons in the conical phase, up to H_{c2}
  - spin-waves within the skyrmion crystal
  - helimagnons under pressure $\rightarrow$ NFL phase
  - polarized TAS $\Rightarrow$ polarization of spin-waves
  - other DM-helimagnets: Cu_2OSeO_3, $Fe_{1-x}Co_xSi$, ...
  - damping of helimagnons

for details, see arXiv:1502.06977 and

thanks for your attention!