Inelastic Neutron Scattering

Mechthild Enderle

Institute Laue-Langevin, Grenoble

September 11, 2019

Outline

- Interaction neutron – matter
- Collective dynamics: Dispersion
- Collective dynamics: Intensities
- More than phonons and spin waves
- Even on powder

Master equation for neutron scattering

- weak interaction $\rightarrow$ single scattering process
- 1st order perturbation - 1st Born approximation - Fermi's golden rule
- incoming/scattered neutron plane wave
- energies far away from nuclear resonances

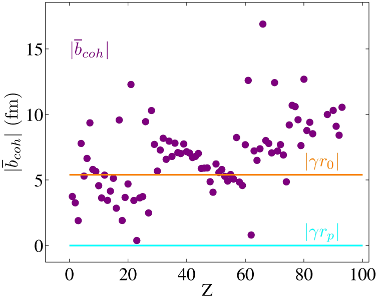
$$\frac{d^2\sigma}{d\Omega dE_f}\Big|_{n_0,\sigma_i \rightarrow n_1,\sigma_f} = \frac{k_f}{k_i}\left(\frac{m}{2\pi\hbar^2}\right)^2 \left|\langle \boldsymbol{k}_f \sigma_f n_1 | V | \boldsymbol{k}_i \sigma_i n_0 \rangle\right|^2 \cdot$$

$$\cdot \delta(\epsilon_1 - \epsilon_0 - \underbrace{(E_i - E_f)}_{\hbar\omega})$$

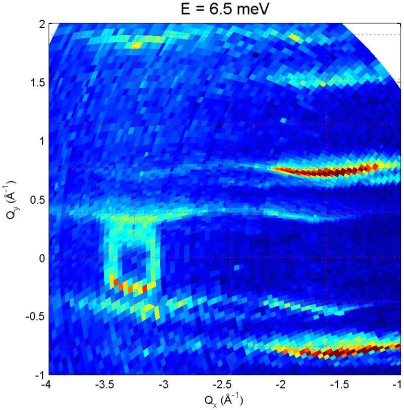
Interactions of neutrons with matter V

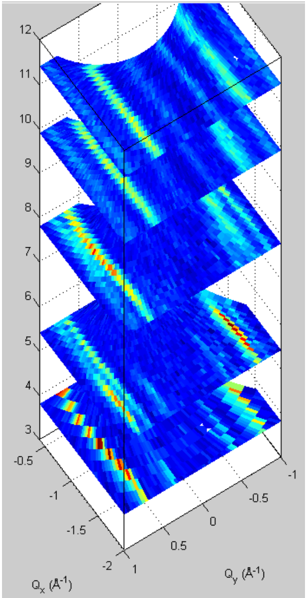
n	–	atomic nucleus	strong interaction
n	–	electronic magn. moment	dipole-dipole interaction
n	–	electric field	spin-orbit + Foldy interaction

	average (absolute) scattering length		
nucleus	$+6.5$	fm	
el. magn. mom.	-5.4	fm	$(\cdot S(J))$
electric field	$+1.5$	am	



Magnetic and lattice excitations: comparable intensity





Nuclear interaction potential

Fermi pseudopotential V_N for neutron scattering from one nucleus

$$V_N(\boldsymbol{r}) = \frac{2\pi\hbar^2}{m}\bar{b}\,\delta(\boldsymbol{r} - \boldsymbol{R}_j)$$

Coherent scattering length $\bar{b}$: average over nuclear spin states and isotopes of an element.

entire sample: $$V_N(\boldsymbol{r}) = \frac{2\pi\hbar^2}{m}\sum_{j=1}^{10^{23}}\bar{b}_j\,\delta(\boldsymbol{r} - \boldsymbol{R}_j) = \frac{2\pi\hbar^2}{m}\,N(\boldsymbol{r})$$

Magnetic interaction potential

magnetic potential V_M for neutron scattering from one electron

$$V_M(\boldsymbol{r}) = -\boldsymbol{\mu}_n \cdot \boldsymbol{B}_e$$

$$V_M(\boldsymbol{r}) = -\boldsymbol{\mu}_n \cdot \nabla \times \boldsymbol{A}$$

$$V_M(\boldsymbol{r}) = -\boldsymbol{\mu}_n \cdot \nabla \times \overbrace{\Big(\underbrace{\nabla \times \frac{\boldsymbol{\mu}_e^S}{r}}_{\text{spin}} + \underbrace{\nabla \times \frac{\boldsymbol{\mu}_e^L}{r}}_{\text{orbital current}} \Big)}^{\text{vector potential } \boldsymbol{A}}$$

Magnetic matrix element - Fourier transform

one electron

$$\langle \boldsymbol{k}_i \sigma_i n_0 | -\boldsymbol{\mu}_n \cdot \nabla \times \left(\nabla \times \frac{\boldsymbol{\mu}_e^{tot}}{r} \right) | \boldsymbol{k}_f \sigma_f n_1 \rangle$$

$$= \langle \sigma_i n_0 | -\boldsymbol{\mu}_n \cdot \underbrace{\left(\hat{\boldsymbol{Q}} \times (\hat{\boldsymbol{Q}} \times \boldsymbol{\mu}_e^{tot}(\boldsymbol{Q})) \right)} | \sigma_f n_1 \rangle$$

$$= \langle \sigma_i n_0 | -\boldsymbol{\mu}_n \cdot \boldsymbol{\mu}_{e\,\perp}^{tot}(\boldsymbol{Q}) | \sigma_f n_1 \rangle$$

entire sample

$$\sum \tilde{\boldsymbol{\mu}}_{e\,\perp}^{tot}(\boldsymbol{Q}) = \boldsymbol{M}_\perp(\boldsymbol{Q})$$

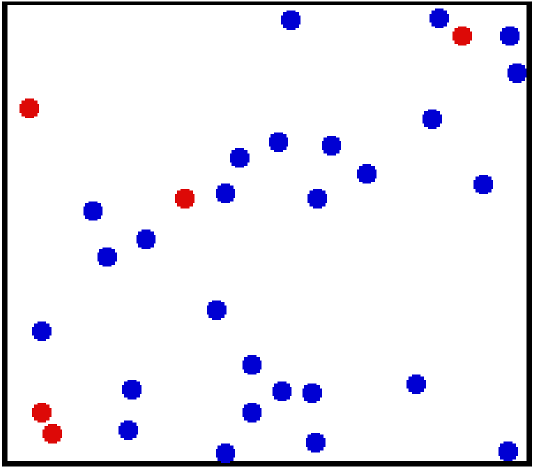
Coherent and incoherent scattering

Coherent scattering	Incoherent scattering
average scattering amplitude	standard deviation of the amplitude
equal objects periodically arranged	unequal objects (periodically arranged) – isotopes – nuclear spin directions – electronic spin directions
interference of different (identical) objects	interference of 1 object with itself
Pair correlation	Autocorrelation

Diffuse (Brownian) motion

Disordered materials
(non-periodic materials)

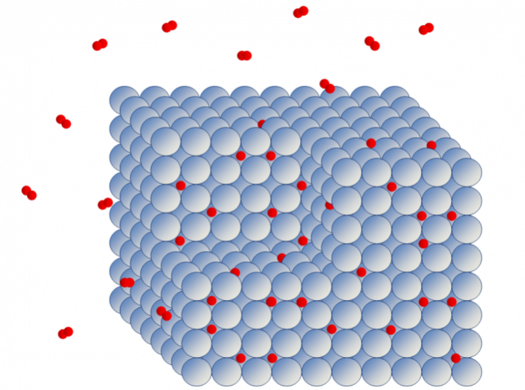
- polymers
- liquids
- macromolecules
- biological cells



Diffuse motion in crystals

Disordered phenomena in crystals

- hydrogen diffusion
- spin diffusion, e.g. critical scattering near a phase transition



Signature of diffuse motion: Quasielastic scattering

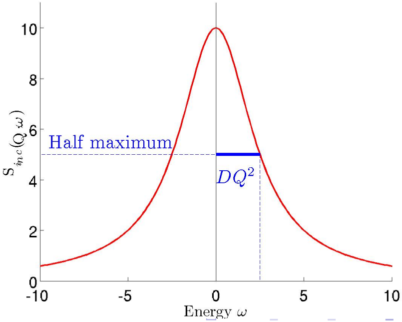
$$\left.\frac{d^2\sigma}{d\omega d\Omega}\right|_{\text{inc}} = \frac{\sigma_{\text{inc}}}{4\pi}\frac{k_f}{k_i} N S_{\text{inc}}(\boldsymbol{Q},\omega)$$

$$S_{\text{inc}}(\boldsymbol{Q},\omega) = \frac{1}{2\pi\hbar}\int dt\; d\boldsymbol{r}\; e^{i(\boldsymbol{Q}\boldsymbol{r}-\omega t)}\; G_{\text{self}}(\boldsymbol{r},t)$$

$$G_{\text{self}}(\boldsymbol{r},t) = \frac{1}{N}\sum_j \int d\boldsymbol{r}'\langle\; \delta(\boldsymbol{r}'-\boldsymbol{R}_j(0))\; \delta(\boldsymbol{r}'+\boldsymbol{r}-\boldsymbol{R}_j(t))\;\rangle_T$$

Incoherent cross section $\sim$ autocorrelation

correlation of a particle/spin at $\boldsymbol{r}=0, t=0$ with the same particle/spin at $\boldsymbol{r}, t$



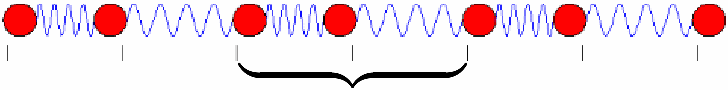
Instruments for Quasielastic scattering

Slow dynamics $\Rightarrow$ high energy resolution

- cold Time Of Flight
- backscattering
- spin echo spectroscopy

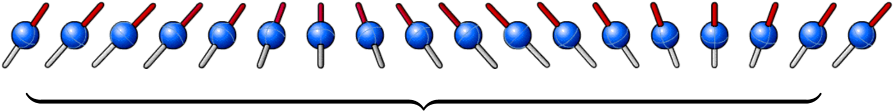
Collective motion – coherent dynamics – "ballet"

phonons



λ

magnons

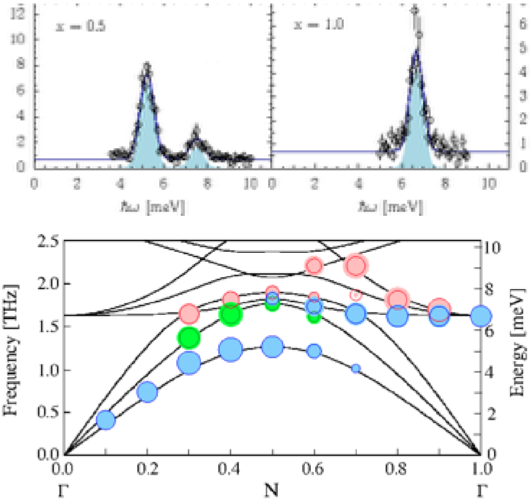


wavelength λ

wave vector $Q = \frac{2\pi}{\lambda}$

Collective dynamics: Signature dispersion

phonons (IN8)



- in periodic arrays/ crystals
- in liquids (sound wave)

Dispersion:

discrete $\hbar\omega$ at each $\boldsymbol{Q}$

M.M. Koza *et al.* PRB **91** 014305 (2015)

Collective motion – wave – interference pattern

Coherent cross section

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right|_{\text{coh}} = \frac{k_f}{k_i}\left(\frac{m}{2\pi\hbar^2}\right)^2 \sum_{n_0,n_1} p(n_0) \left| \langle n_1 | V(\boldsymbol{Q}) | n_0 \rangle \right|^2 \delta(\varepsilon_1 - \varepsilon_0 - \hbar\omega)$$

$$= \frac{k_f}{k_i}\underbrace{\left(\frac{m}{2\pi\hbar^2}\right)^2 \sum_{n_0} p(n_0) \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} dt\, e^{-i\omega t} \langle n_0 \,|\, V^*(\boldsymbol{Q},0) V(\boldsymbol{Q},t) \,|\, n_0 \rangle}$$

$$= \frac{k_f}{k_i} \quad S(\boldsymbol{Q},\omega)$$

coherent dynamic scattering function

Coherent dynamic scattering function

$$S_N(\boldsymbol{Q},\omega) = \sum_{n_0} p(n_0)\frac{1}{2\pi\hbar}\int dt\ e^{-i\omega t}\ \langle n_0|\ N^*(\boldsymbol{Q},0)N(\boldsymbol{Q},t)\ |n_0\rangle$$

$$= \frac{1}{2\pi\hbar}\int d\boldsymbol{r}dt\ e^{i(\boldsymbol{Q}\boldsymbol{r}-\omega t)}\ \langle\ N(\boldsymbol{0},0)N(\boldsymbol{r},t)\ \rangle_T$$

$$S_M(\boldsymbol{Q},\omega) = \sum_{n_0} p(n_0)\frac{(\gamma r_0)^2}{2\pi\hbar}\int dt\ e^{-i\omega t}\ \langle n_0|\ \boldsymbol{M}_\perp^*(\boldsymbol{Q},0)\boldsymbol{M}_\perp(\boldsymbol{Q},t)\ |n_0\rangle$$

$$= \frac{(\gamma r_0)^2}{2\pi\hbar}\int d\boldsymbol{r}dt\ e^{i(\boldsymbol{Q}\boldsymbol{r}-\omega t)}\ \langle\ \boldsymbol{M}_\perp(\boldsymbol{0},0)\cdot\boldsymbol{M}_\perp(\boldsymbol{r},t)\ \rangle_T$$

$S(\boldsymbol{Q},\omega)$ is the space-time Fourier transform of the

nuclear-positional
magnetic

density-density pair correlation function

Coherent and incoherent scattering

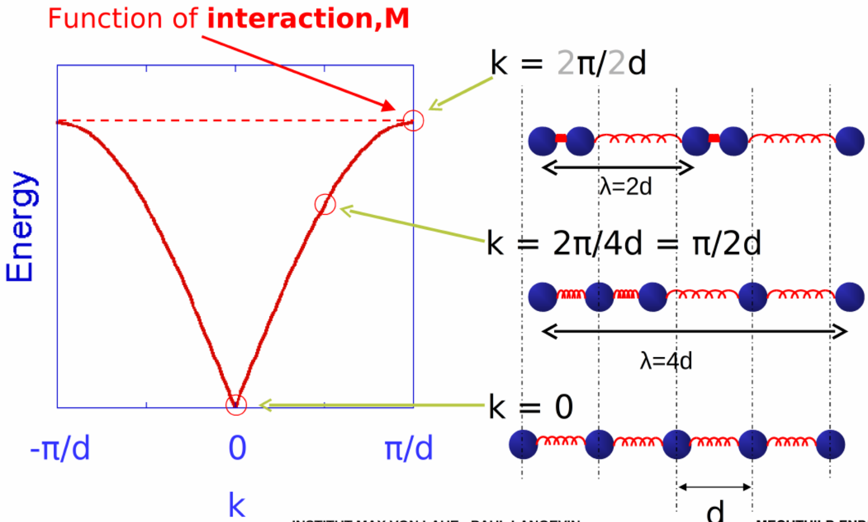
Coherent cross section	Incoherent cross section
$\sim$ pair correlation function:	$\sim$ 1-particle autocorrelation:
$\rightarrow$ dispersion relation	$\rightarrow$ diffusion coefficient
$\rightarrow$ structural pattern	no structural information

Collective dynamics	Brownian motion
atoms/magnetic moments move "correlated" ("ballet")	"random walk" uncorrelated, diffuse motion
Snapshot: periodic pattern – wave	disordered

Collective dynamics in the incoherent cross section:

$\sim$ density of states $Z(\omega)$ – loss of all structural information

Collective excitations of the lattice: phonons



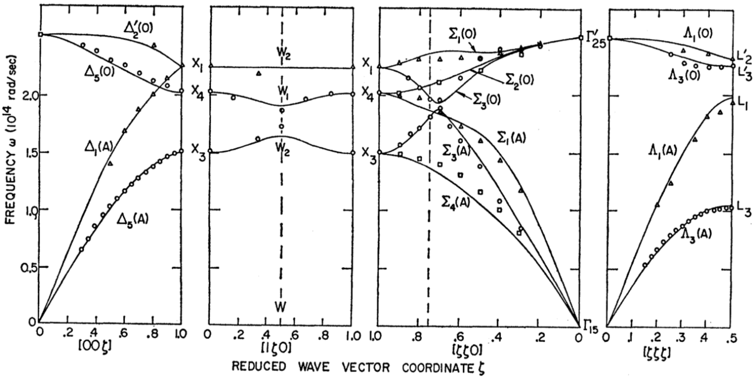
INSTITUT MAX VON LAUE - PAUL LANGEVIN

MECHTHILD ENDERLE

Phonons in diamond

diamond:  covalent bonds

1000 meV

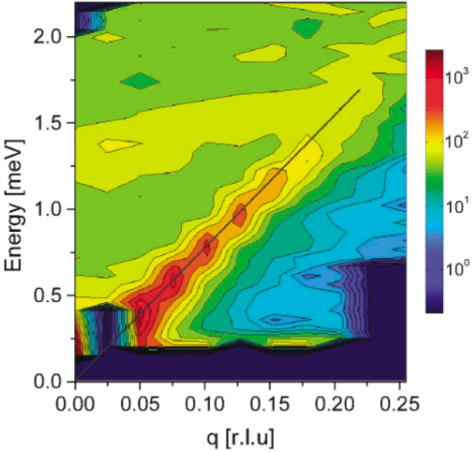


J.L. Warren *et al.* Phys.Rev. **158** 805 (1967)

Phonons in bcc ^{4}He

bcc ^{4}He  van der Waals (+quantum effects)

1 meV



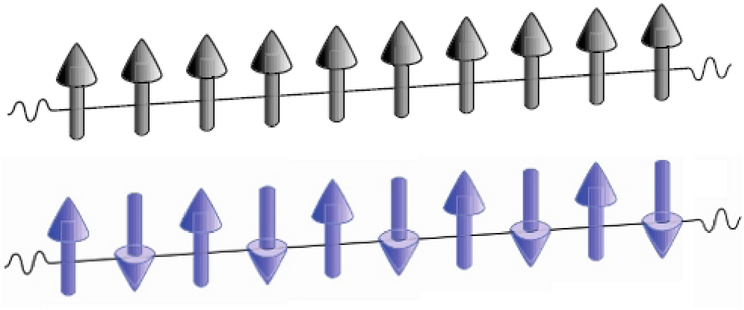
$T = 1.6400(1)$K

IN12

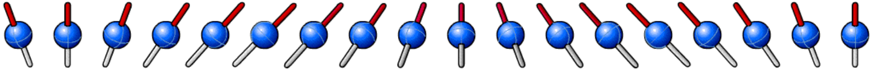
M. Markovich *et al.* PRL **88** 195301 (2002)

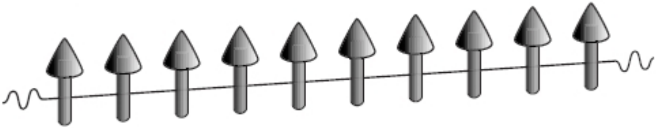
"Magnetic springs" - mostly super-exchange

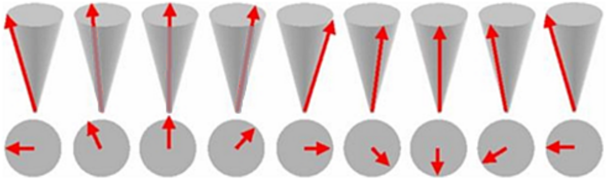
may favor parallel / antiparallel magnetic moments: Ferromagnet / Antiferromagnet



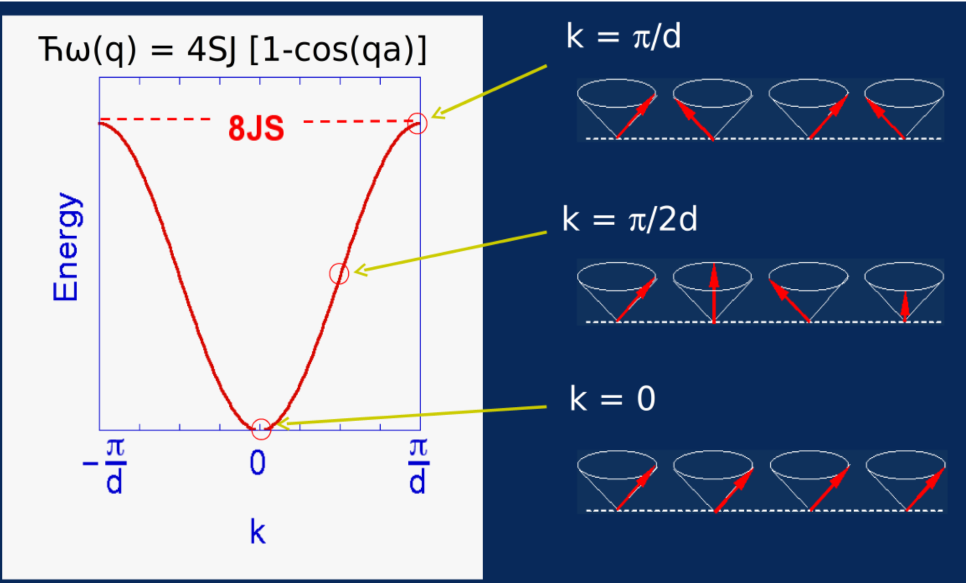
Spin waves in a ferromagnet



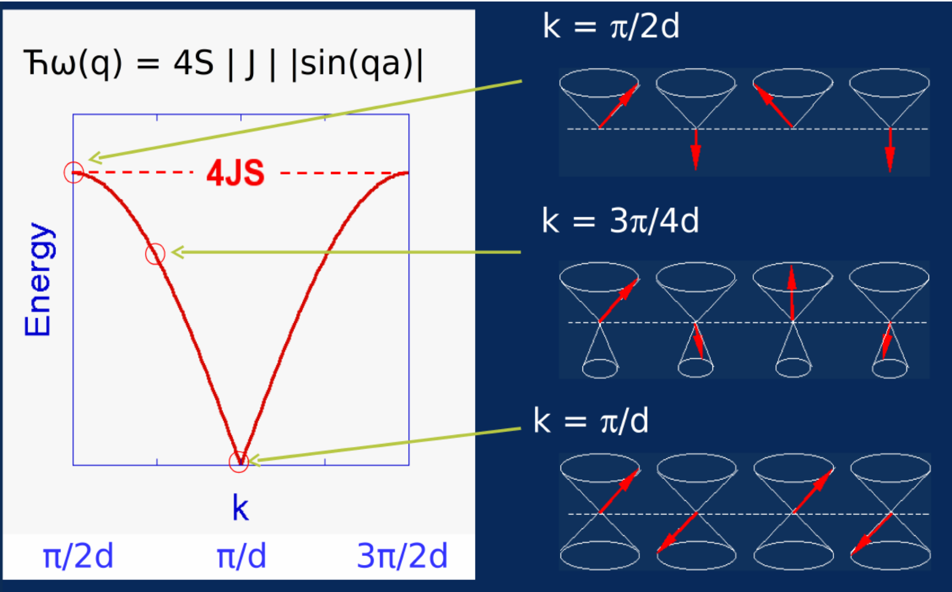




Collective excitations of the ferromagnet: magnons

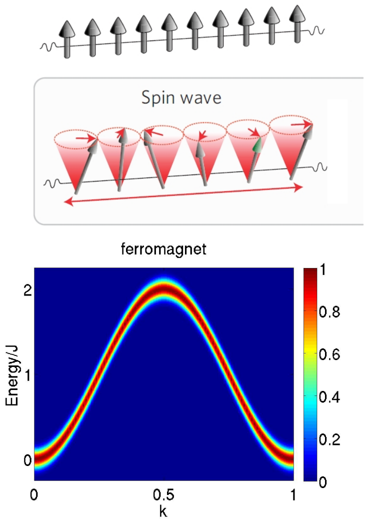


Magnons in the "classical" antiferromagnet

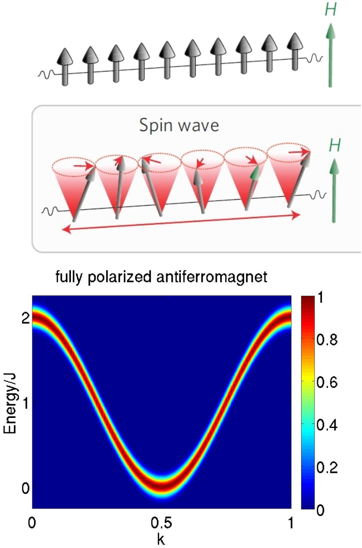


Magnon dispersion reveals microscopic interactions

Ferromagnet



Saturated antiferromagnet $H > H_{\text{sat}}$

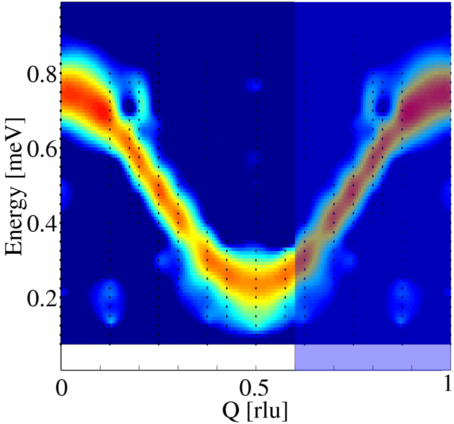


Magnon dispersion reveals microscopic interactions

$CuSO_4.5D_2O$

$H > H_{\text{sat}}$

no long range order >0.1K



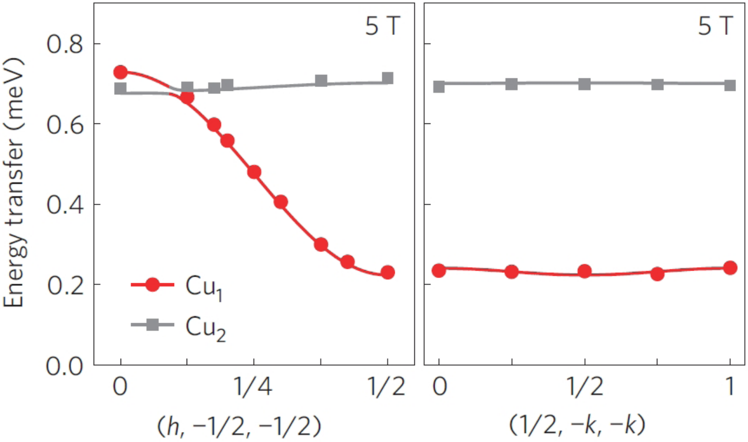
$\Uparrow$

antiferromagnetic exchange

Magnon dispersion reveals microscopic interactions

$CuSO_4.5D_2O$ fully saturated $H > H_{sat}$

magnetic springs only in one direction



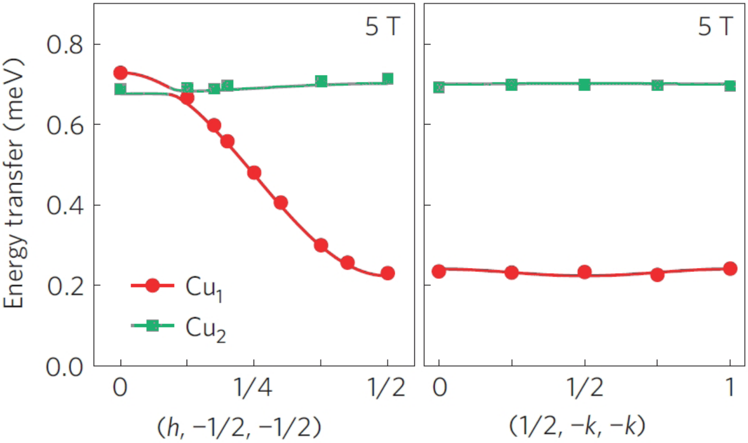
magnetically 1D !

M. Mourigal, M.E. *et al.* Nat. Phys. **9** 435 (2013)

Magnon dispersion reveals microscopic interactions

$CuSO_4.5D_2O$ fully saturated $H > H_{\text{sat}}$

no springs/ no interaction: local transition

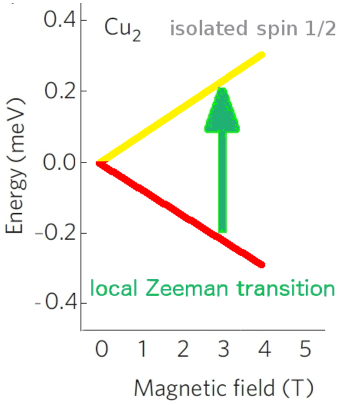


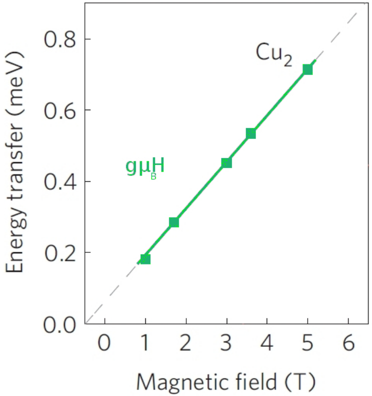
no springs

Energy independent of Q for all directions of Q

Local spin flip between Zeeman-split states

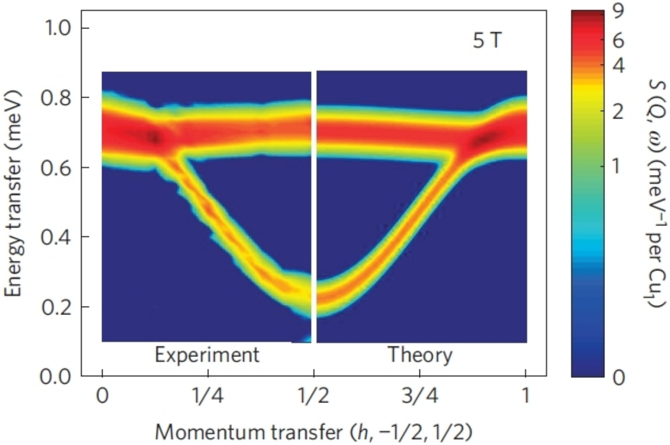
$CuSO_4.5D_2O$





M. Mourigal, M.E. *et al.* Nat. Phys. **9** 435 (2013).

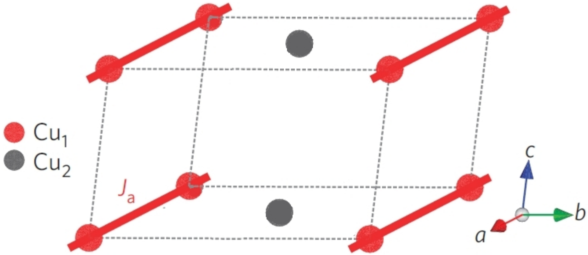
Fully saturated $CuSO_4.5D_2O$



M. Mourigal, M.E. *et al.* Nat. Phys. **9** 435 (2013).

Spin waves in fully saturated $CuSO_4.5D_2O$

→ microscopic scheme of magnetic interactions



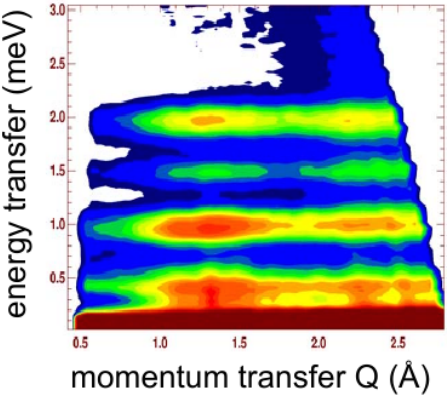
Cu_1: one-dimensional arrays with antiferromagnetic interaction
Cu_2: not coupled by any interaction

M. Mourigal, M.E. *et al.* Nat. Phys. **9** 435 (2013).

Local excitations: infinitely weak "springs"

Signature: flat dispersion

$CsFe_8$ IN5



- Molecular magnets
- Crystal field excitations (Rare Earth)

O. Waldmann, APS lecture 2006

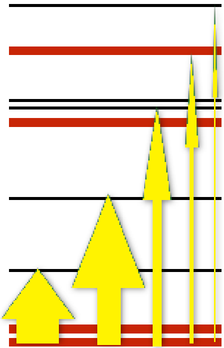
Local transitions: Crystal Electric Field Splitting

$Tb_2Ti_2O_7$

Tb^{3+}:

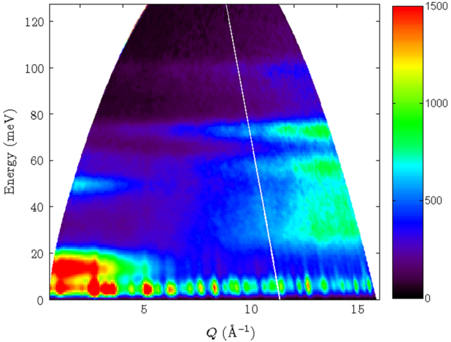
$$^7F_6 \quad \left\{ \begin{array}{c} S = 3 \\ L = 3 \end{array} \right\} \quad J = 6$$

Stark effect



Merlin $E_i = 150$meV

powder, $T = 7$K



CF phonons

A. J. Princep *et al.* PRB **91** 224430 (2015).

Collective dynamics

atoms/magnetic moments move "correlated" ("ballet")

Snapshot: periodic pattern – wave

Positions of the nuclei

Local:
vibrational scattering
rattling modes

Propagating:
phonons

Direction/Length of the magnetic moment

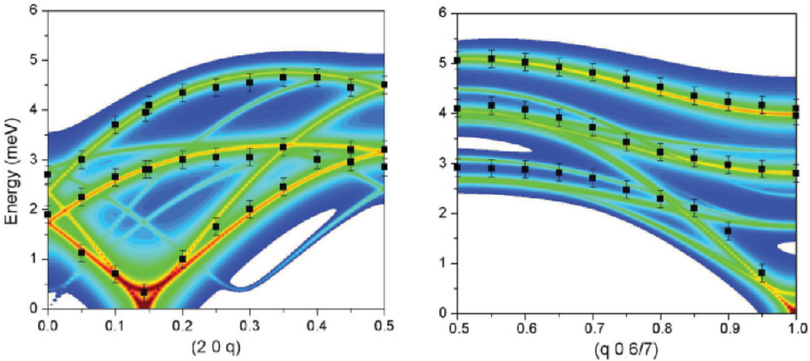
Local:
C(rystal)F(ield)-excitations
transitions in molecular magnets

Propagating:
spin waves (magnons)
triplons
spinons
phasons
multi-magnon/-spinon states

[. . . and hybrid states . . .]

Reality is not always so simple . . .

J. Jensen (2011) PRB 84, 104405



Quantitative info from intensities: Coherent dynamic scattering function

$$S_N(\boldsymbol{Q},\omega) = \frac{1}{2\pi\hbar}\int d\boldsymbol{r}dt\; e^{i(\boldsymbol{Q}\boldsymbol{r}-\omega t)} \langle\; N(\boldsymbol{0},0)N(\boldsymbol{r},t)\;\rangle_T$$

$$S_M(\boldsymbol{Q},\omega) = \frac{(\gamma r_0)^2}{2\pi\hbar}\int d\boldsymbol{r}dt\; e^{i(\boldsymbol{Q}\boldsymbol{r}-\omega t)} \langle\; \boldsymbol{M}_\perp(\boldsymbol{0},0)\cdot\boldsymbol{M}_\perp(\boldsymbol{r},t)\;\rangle_T$$

$S(\boldsymbol{Q},\omega)$: space-time Fourier transform of the

nuclear-positional / magnetic — density-density pair correlation function

- quantitative info from intensity
- phonon and magnetic scattering (often) well separated

Intensities - phonons

$$S_N(\boldsymbol{Q},\omega) = \sum_{n_0} p(n_0) \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} dt\ e^{-i\omega t} \langle\ n_0 |\ N^*(\boldsymbol{Q},0) N(\boldsymbol{Q},t)\ |\ n_0 \rangle$$

$$S_N^{1ph}(\boldsymbol{Q},\omega) = \sum_{s=1}^{3r} |I_{N,s}(\boldsymbol{Q})|^2 \left[\langle n_s + 1 \rangle_T \delta(\omega - \omega_s) + \langle n_s \rangle_T \delta(\omega + \omega_s) \right]$$

$$\langle n_s + 1 \rangle_T = \frac{1}{1 - e^{-\frac{\hbar\omega_s}{k_B T}}}$$

$$\langle n_s \rangle_T = \frac{e^{-\frac{\hbar\omega_s}{k_B T}}}{1 - e^{-\frac{\hbar\omega}{k_B T}}}$$

Intensities - phonons

$$S_N(\boldsymbol{Q},\omega) = \sum_{n_0} p(n_0)\frac{1}{2\pi\hbar}\int_{-\infty}^{\infty} dt\; e^{-i\omega t}\,\langle\, n_0 |\; N^*(\boldsymbol{Q},0)N(\boldsymbol{Q},t)\;|\; n_0\rangle$$

$$S_N^{1ph}(\boldsymbol{Q},\omega) = \sum_{s=1}^{3r} |I_{N,s}(\boldsymbol{Q})|^2\,[\langle n_s+1\rangle_T\delta(\omega-\omega_s)+\langle n_s\rangle_T\delta(\omega+\omega_s)]$$

$$|I_{N,s}(\boldsymbol{Q})|^2 = \frac{1}{\omega_s}\left|\underbrace{\sum_{j=1}^{r}\frac{\overline{b_j}}{\sqrt{M_j}}\,e^{-W_j}\,e^{i\boldsymbol{Q}\boldsymbol{d}_j}}_{\text{FT of points } \boldsymbol{d}_j}\qquad\underbrace{(\boldsymbol{Q}\cdot\boldsymbol{e}_{js})}_{\text{increases with } Q^2}\right|^2$$

Intensity periodic if $\boldsymbol{d}_j$ special position

$\boldsymbol{e}_{js}$: amplitude atom j, phonon s

Intensities - magnons, $T \ll T_N$

$$S_M(\boldsymbol{Q},\omega) = (\gamma r_0)^2 \sum_{n_0} p(n_0) \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} dt\ e^{-i\omega t} \langle\ n_0 |\ \boldsymbol{M}_\perp^*(\boldsymbol{Q},0)\boldsymbol{M}_\perp(\boldsymbol{Q},t)\ |\ n_0 \rangle$$

$$S_M^{1m}(\boldsymbol{Q},\omega) = \sum_{s=1}^{r} |I_{M,s}(\boldsymbol{Q})|^2 \left[\langle n_s + 1\rangle_T \delta(\omega - \omega_s) + \langle n_s \rangle_T \delta(\omega + \omega_s)\right]$$

$$\langle n_s + 1\rangle_T = \frac{1}{1 - e^{-\frac{\hbar\omega_s}{k_B T}}}$$

$$\langle n_s \rangle_T = \frac{e^{-\frac{\hbar\omega_s}{k_B T}}}{1 - e^{-\frac{\hbar\omega}{k_B T}}}$$

Intensities - magnons, $T \ll T_N$

$$S_M(\boldsymbol{Q},\omega) = (\gamma r_0)^2 \sum_{n_0} p(n_0) \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} dt\ e^{-i\omega t} \langle\ n_0 |\ \boldsymbol{M}_\perp^*(\boldsymbol{Q},0)\boldsymbol{M}_\perp(\boldsymbol{Q},t)\ |\ n_0 \rangle$$

$$S_M^{1m}(\boldsymbol{Q},\omega) = \sum_{s=1}^{r} |I_{M,s}(\boldsymbol{Q})|^2 \left[\langle n_s + 1\rangle_T \delta(\omega-\omega_s) + \langle n_s\rangle_T \delta(\omega+\omega_s)\right]$$

$$|I_{M,s}(\boldsymbol{Q})|^2 = (\gamma r_0)^2 \left| \sum_{j=1}^{r} \underbrace{f_j(\boldsymbol{Q})}_{\text{form factor}}\ e^{-W_j}\ e^{i\boldsymbol{Q}\boldsymbol{d}_j} \underbrace{\boldsymbol{e}_{\perp,js}}_{\text{mag. amp. ion } j \text{, magnon } s} \right|^2$$

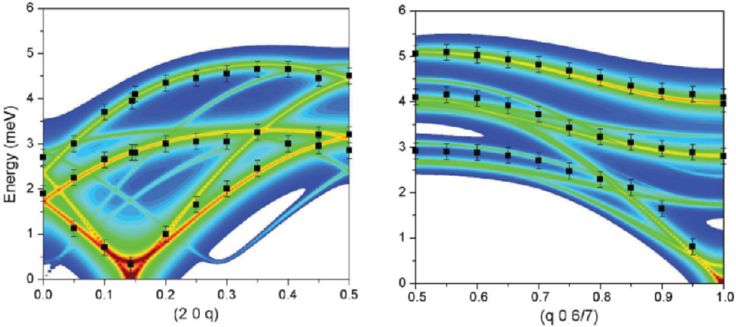
Intensity periodic if $\boldsymbol{d}_j$ special position

Magnon intensities

...often essential to assign a spin wave branch to a peak !

Long-range ordered structures
length of ordered moment identical at equivalent sites
transverse excitations
"Classical" Spin Wave Theory

J. Jensen (2011) PRB 84, 104405



Magnetic excitations: more than spin waves

So far:

Ground state: periodically ordered atoms or magnetic moments

Collective excitations:

phonons spin waves	small oscillations around the	structural magnetic	order

Now:

periodically ordered magnetic sites with a local magnetic moment

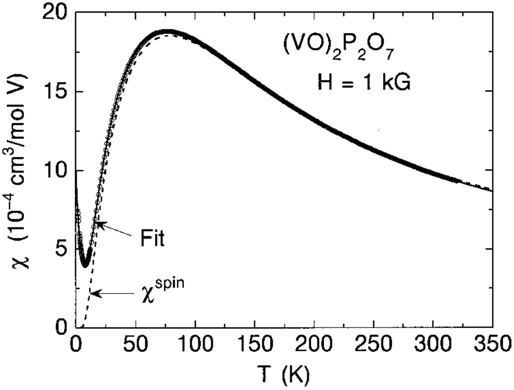
interaction between the spins (e.g. visible in $\chi(T)$)

no long-range ordered magnetic moment

Collective excitations ?

Collective phenomena without magnetic long-range order

χ displays interactions – but no phase transition



Two spins $\frac{1}{2}$ and an antiferromagnetic spring

$S = \frac{1}{2}$ at each site

strong antiferromagnetic	coupling between	next-neighbours
no	coupling between	pairs

Dimer: Pair spin 0 $\frac{1}{\sqrt{2}} \left[\, |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \, \right]$

Local singlet-triplet excitations

$S = \frac{1}{2}$ at each site

strong antiferromagnetic coupling between next-neighbours

no coupling between pairs

Triplon: Pair spin 1

$$\left\{ \begin{array}{c} |\uparrow\uparrow\rangle \\ \frac{1}{\sqrt{2}} \left[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \right] \\ |\downarrow\downarrow\rangle \end{array} \right.$$

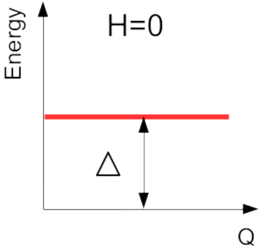
Triplons – Signature Zeeman splitting

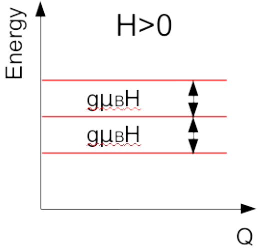
$S = \frac{1}{2}$ at each site

strong antiferromagnetic coupling between next-neighbours

no coupling between pairs

$$\left.\begin{array}{c} |\uparrow\uparrow\rangle \\ \frac{1}{\sqrt{2}} \left[\, |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \,\right] \\ |\downarrow\downarrow\rangle \end{array}\right\}$$



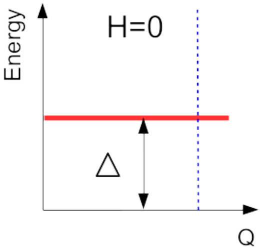


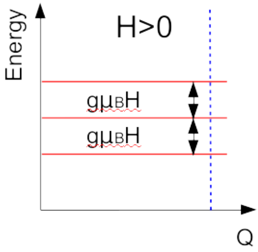
Triplons – Signature Zeeman splitting

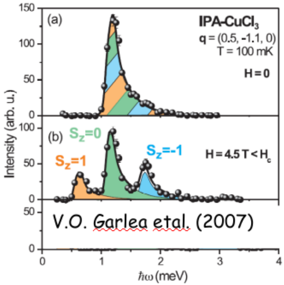
$S = \frac{1}{2}$ at each site

strong antiferromagnetic coupling between next-neighbours

no coupling between pairs



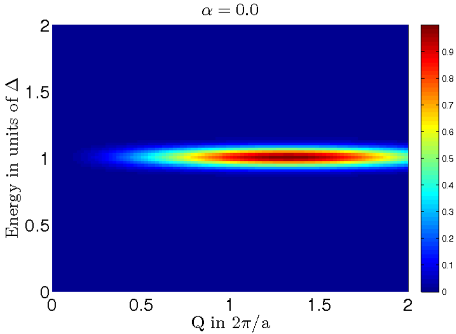




Non-Interacting triplons – intensity signature

$S = \frac{1}{2}$ at each site

strong antiferromagnetic	coupling between	next-neighbours
no	coupling between	pairs

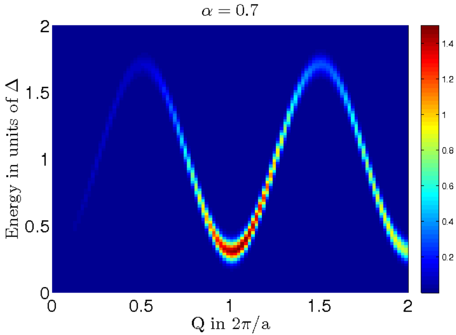


Interacting triplons – propagation – dispersion

$S = \frac{1}{2}$ at each site

strong antiferromagnetic coupling between next-neighbours

increasing coupling between pairs

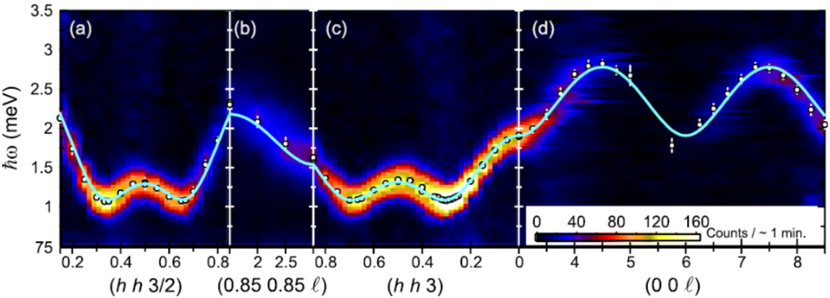


Interacting triplons – propagation – dispersion

$S = \frac{1}{2}$ at each site

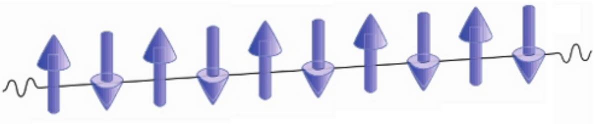
strong antiferromagnetic coupling between next-neighbours

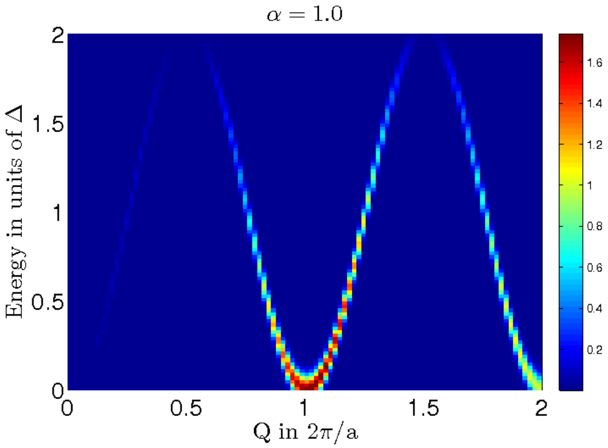
increasing coupling between pairs



M.B. Stone *et al.* PRL **100** 237201 (2008)

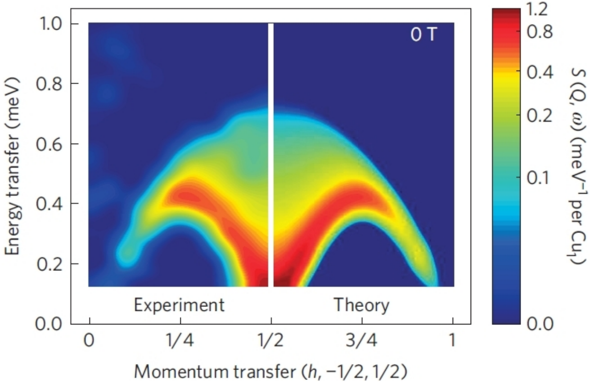
1D array – Limit of uniform coupling between $S = \frac{1}{2}$





1D array – Limit of uniform coupling between $S = \frac{1}{2}$

$H = 0$



M. Mourigal, M.E. *et al.* Nat.Phys. **9** 435 (2013)

Weakly coupled dimer array

Ground state

Triplon

Stronger coupled dimer array

Ground state

Triplon

Stronger coupled dimer array

Ground state

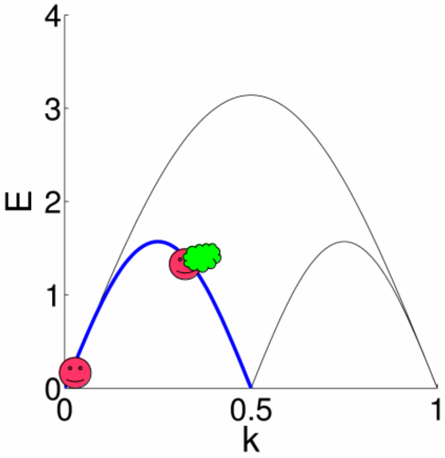
Triplon

1D $S = \frac{1}{2}$ dimer array – Limit of uniform coupling

freely propagating spin $\frac{1}{2}$ particles: spinons

Two-particle excitation: Signature continuous scattering

Neutron excites **pairs** of freely propagating spin $\frac{1}{2}$ particles



1-particle dispersion

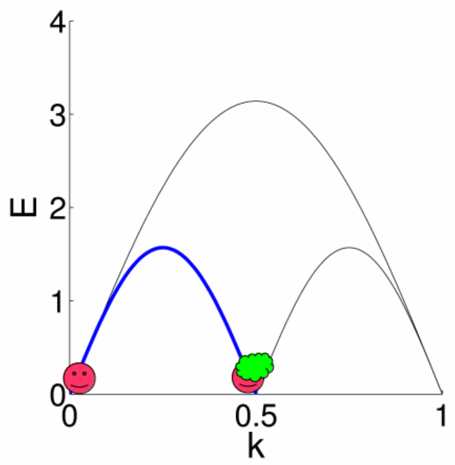
$E(k)$

neutron excites pair

$$Q = k_1 + k_2$$
$$E = E(k_1) + E(k_2)$$

Two-particle excitation: Signature continuous scattering

Neutron excites **pairs** of freely propagating spin $\frac{1}{2}$ particles



1-particle dispersion

$E(k)$

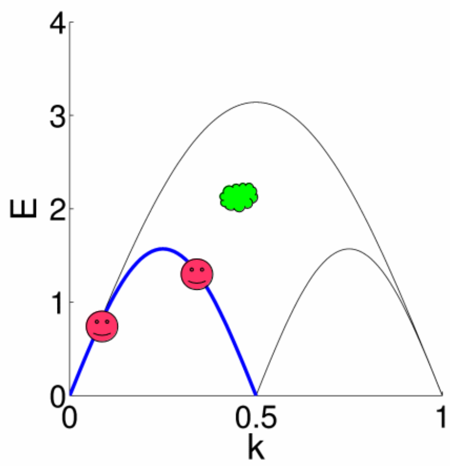
neutron excites pair

$= \quad + $

$$Q = k_1 + k_2$$
$$E = E(k_1) + E(k_2)$$

Two-particle excitation: Signature continuous scattering

Neutron excites **pairs** of freely propagating spin $\frac{1}{2}$ particles



1-particle dispersion

 $E(k)$

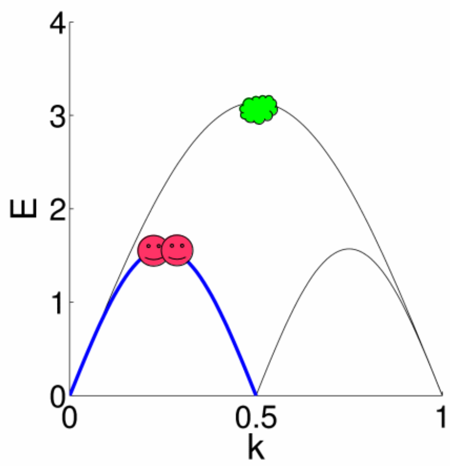
neutron excites pair

 $=$  $+$ 

$$Q = k_1 + k_2$$
$$E = E(k_1) + E(k_2)$$

Two-particle excitation: Signature continuous scattering

Neutron excites **pairs** of freely propagating spin $\frac{1}{2}$ particles



1-particle dispersion

$E(k)$

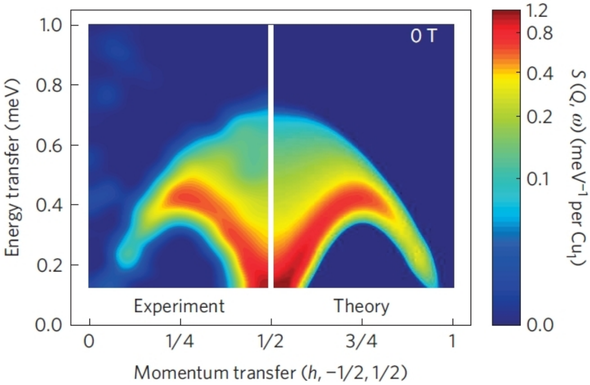
neutron excites pair

$=\ +$

$$Q = k_1 + k_2$$
$$E = E(k_1) + E(k_2)$$

Spinon continuum in $CuSO_4.5D_2O$

$H = 0$



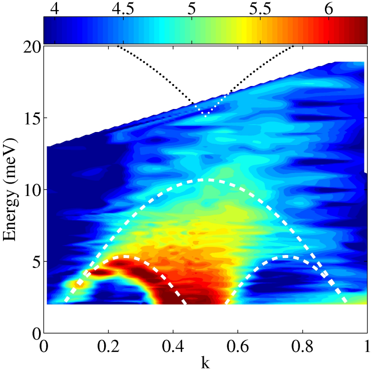
M. Mourigal, M.E. *et al.* Nat.Phys. **9** 435 (2013)

New many-particle states and excitations

2 zig-zag coupled 1D spin $\frac{1}{2}$ arrays

Continuum:
pairs of free particles

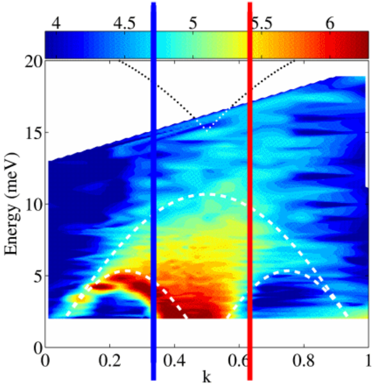
discrete branch:
bound particle-pairs

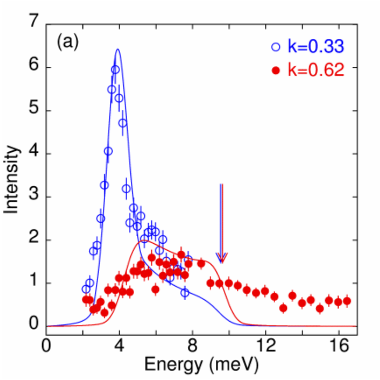


M.E. *et al.* PRL **104** 237207 (2010)

New many-particle states and excitations

2 zig-zag coupled 1D spin $\frac{1}{2}$ arrays

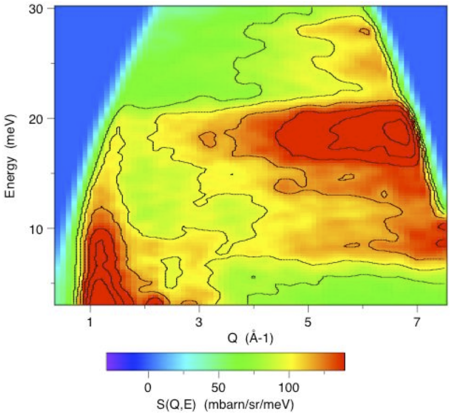




M.E. *et al.* PRL **104** 237207 (2010)

Collective excitations – powder samples

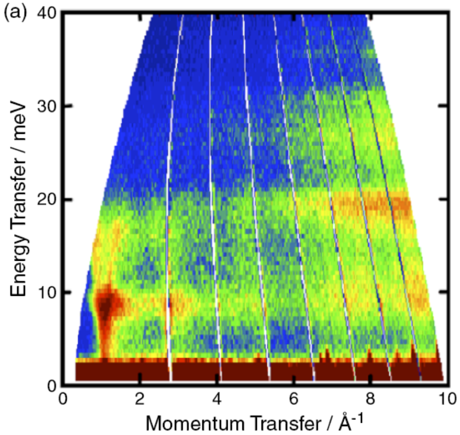
Continuum



B. Fåk *et al.* EPL **81** 17006 (2008)

Deuteronium jarosite

magnons

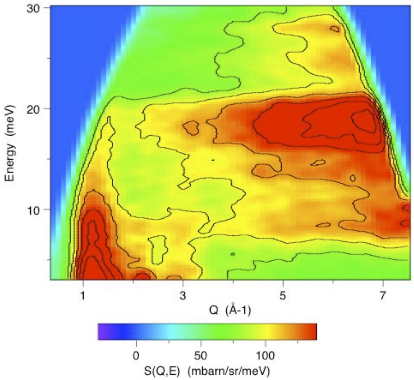


F. Coomer *et al.* JPCM **18** 8847 (2006)

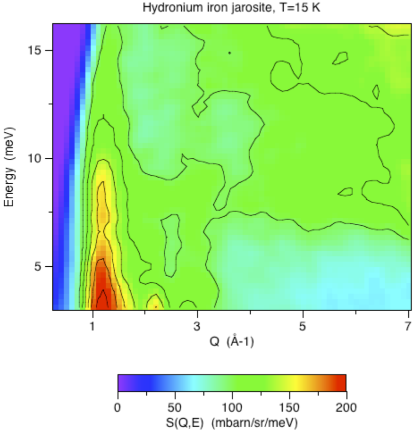
K-jarosite

Collective excitations – powder samples

IN5: deuteronium jarosite powder



magnetic only

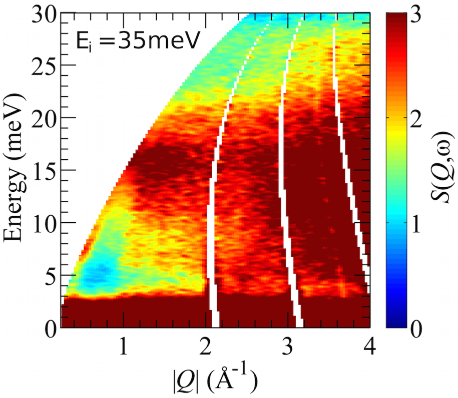


B. Fåk *et al.* EPL **81** 17006 (2008)

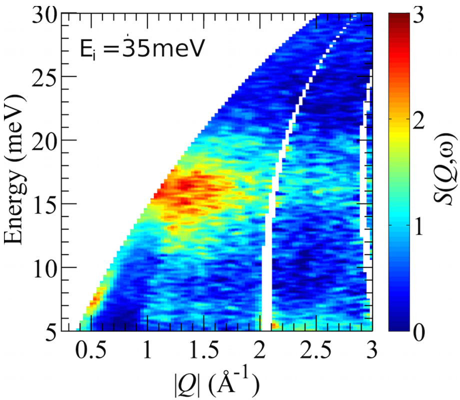
Malachite Inelastic neutron scattering on deuterated powder

MARI/ISIS

all data



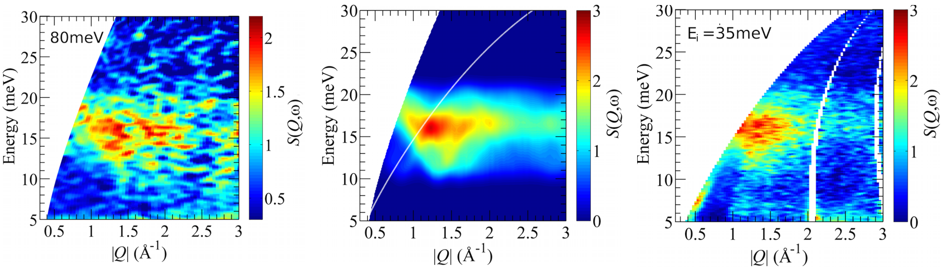
magnetic part



Malachite Inelastic neutron scattering on D-powder

Extracting information from powder samples: Triplons

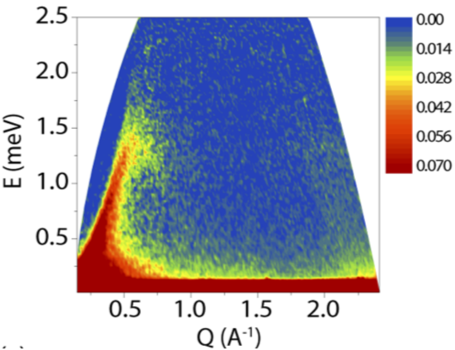
magnetic $E_i = 35$meV | model | magnetic $E_i = 80$meV



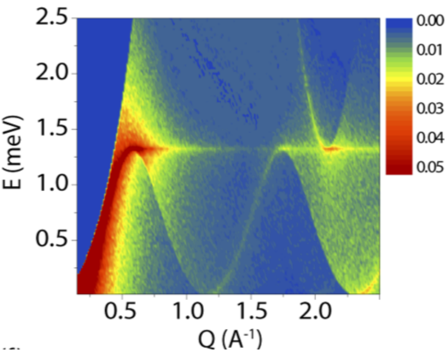
Collective excitations – powder samples: magnons

Extracting information from powder samples: Spinwaves/Magnons

IN5 Haydeite



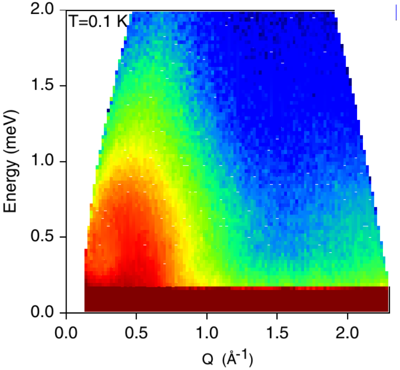
Spin wave theory



D. Boldrin, B. Fåk, M.E., *et al.* PRB **91** 220408 (2015)

Collective excitations – powder samples

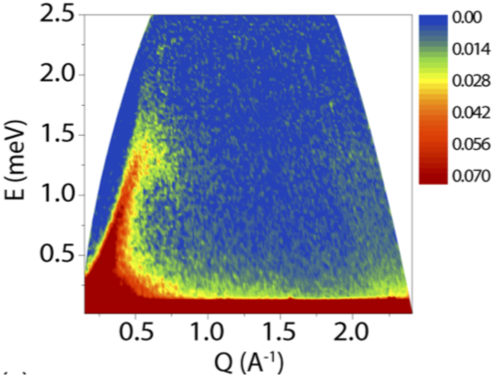
Continuum



B. Fåk *et al.*
PRL **109** 037208 (2012)

IN5 Kapellasite

Magnons

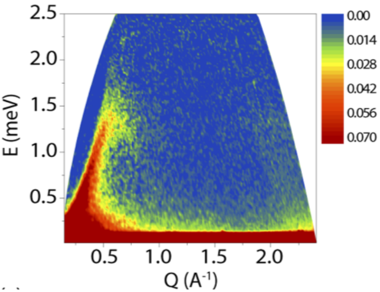


D. Boldrin, B. Fåk, M.E. *et al.*
PRB **91** 220408 (2015)

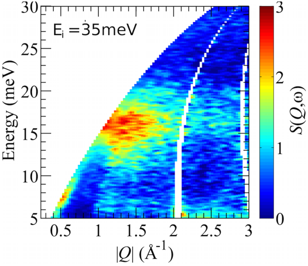
IN5 Haydeite

Collective excitations – powder samples

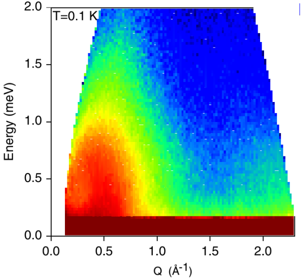
Magnons



Triplons

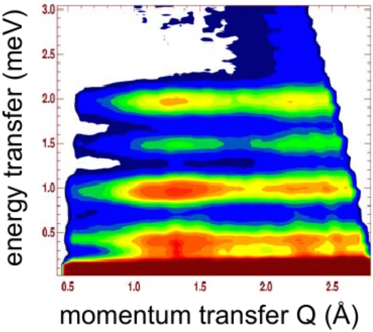


Continuum

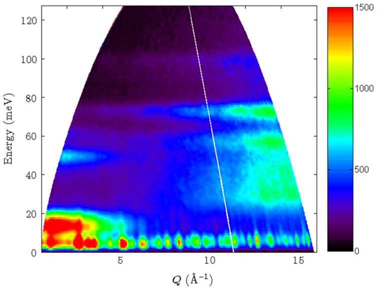


Collective excitations – powder samples

local excitations
(molecule-spin states)



local (Crystal field)
and phonons



Correlated Excitations – How do we measure them ?

- powder on TOF – valuable info
- single crystal TOF – large overview of Q-E-space
- Questions at specific Q/H,p,T: TAS
- Small single crystal: TAS
- inelastic polarized: TAS (today !)