Introduction to Inelastic Neutron Scattering

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National School on Neutron and X-ray Scattering 2013

Outline

1. Fundamental excitations in solids
   - phonons
   - spin-waves (and more)
2. The basic techniques
   - triple-axis
   - time-of-flight
3. A few case studies

Basic experimental considerations

For measuring ***fundamental excitations in solids***, one of the most important tools is ***inelastic neutron scattering.***

Advantages over inelastic x-ray scattering:

1) Neutrons achieve better energy resolution
   - especially with cold neutrons (down to few μeV)

2) Neutrons have large (and well understood) scattering cross-section with magnetic moments (-- neutrons rule magnetism!)

Disadvantages of neutron scattering:

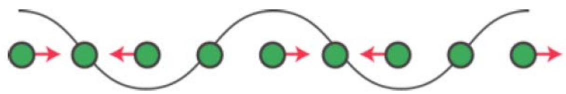
1) typically require large samples/crystals

2) cannot take advantage of x-ray resonant scattering

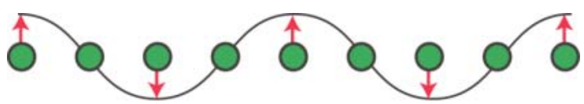
A couple excitations of interest in solids: ***phonons*** and ***spin-waves***

Let's start with **phonons**:

- a collective motion of atoms in a solid
- the normal modes of vibration may be longitudinal or transverse (In liquids, only longitudinal excitations can propagate. Here, I will only focus on solids.)



longitudinal

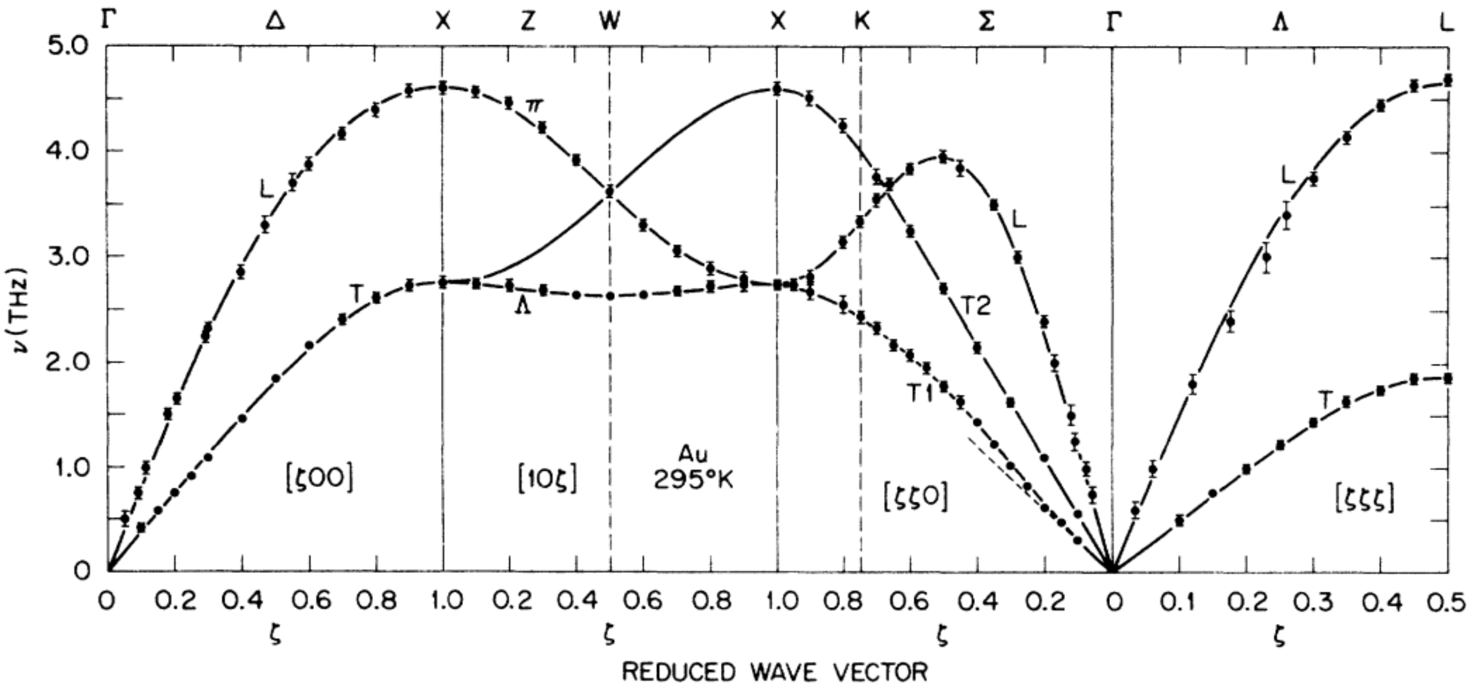


transverse

Measuring the phonons can tell us about

- interatomic potentials & bonding
- structural phase transitions (soft modes)
- many-body physics (eg. electron-phonon coupling)

Phonon dispersion relation in gold



J. W. Lynn, H. G. Smith, and R. M. Nicklow, *Phys. Rev. B* **8**, 3493 (1973).

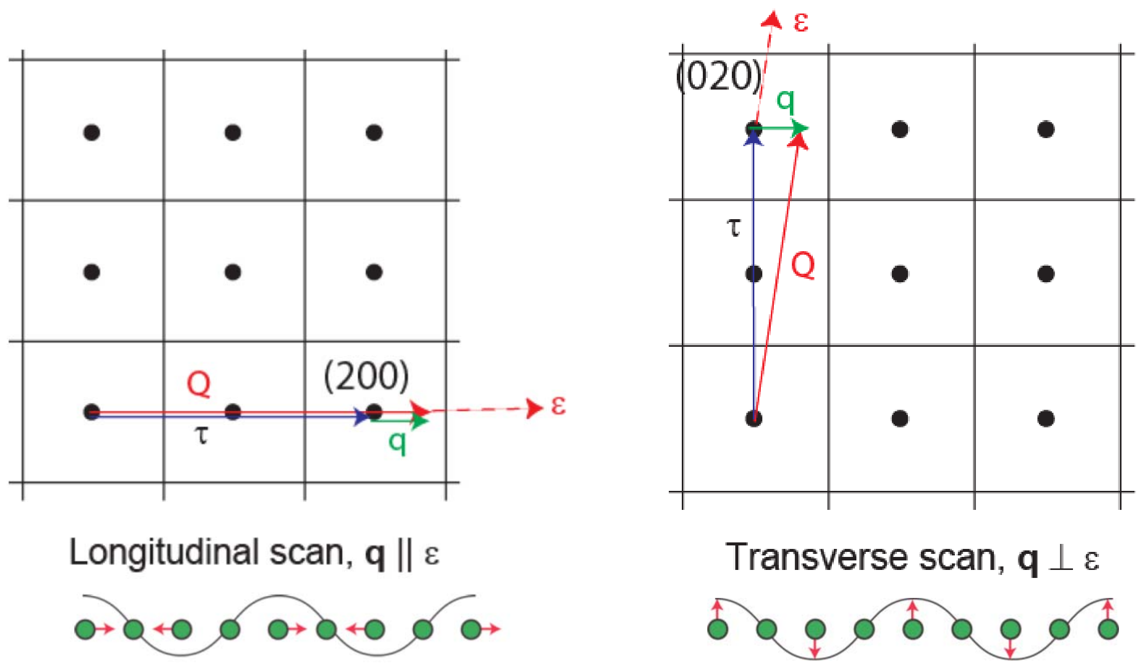
The scattering cross section (coherent, one-phonon)

$$\frac{d^2\sigma}{d\Omega dE_f} = \frac{\sigma_{scat}}{4\pi}\frac{k_f}{k_i} NS(\mathbf{Q},\omega)$$

Structure (polarization) factor

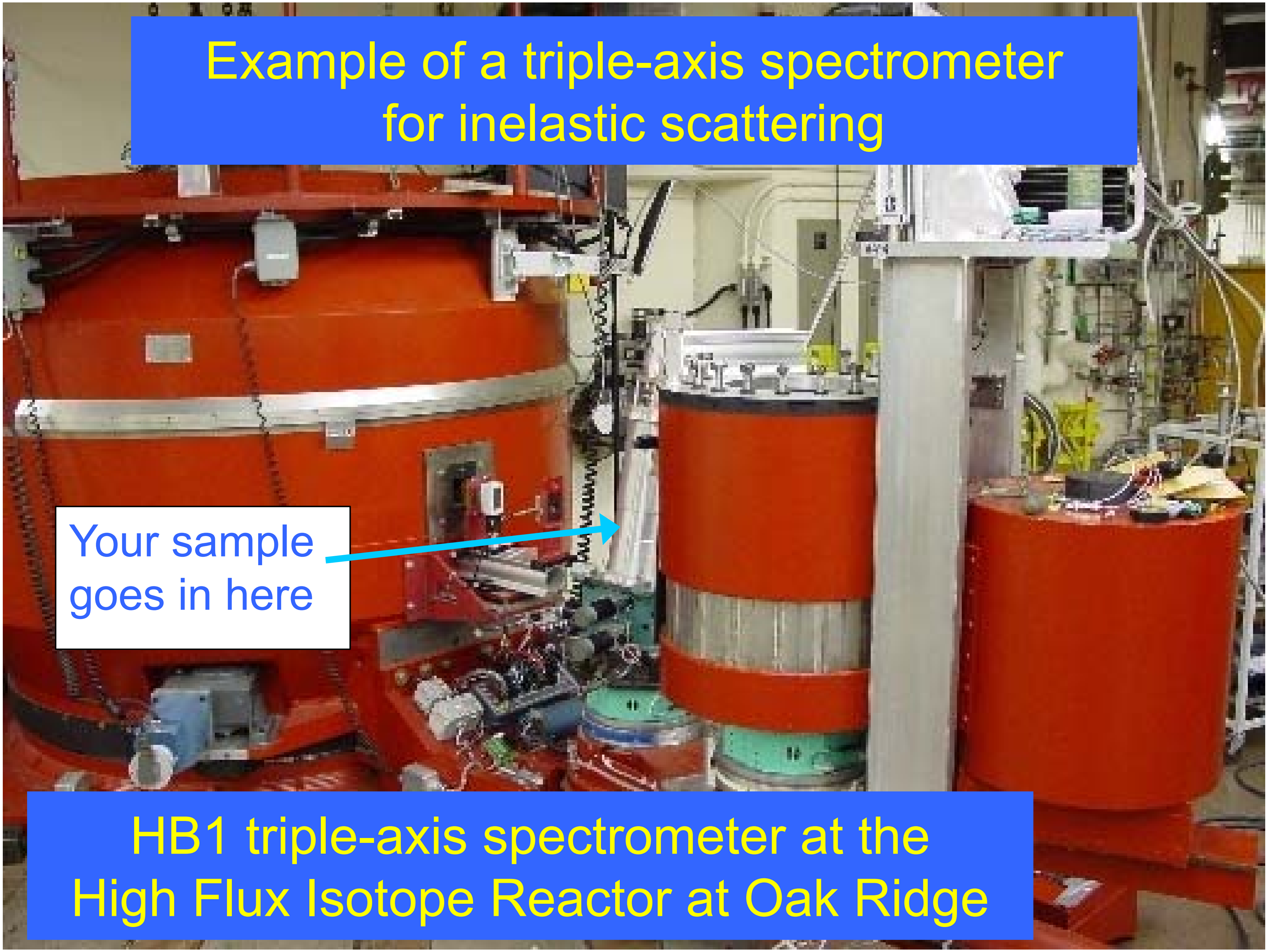
$$S_{1+}(\mathbf{Q},\omega) = \frac{1}{2NM} e^{-Q^2\langle u^2\rangle} \sum_{j\mathbf{q}} \frac{|\mathbf{Q}\cdot\boldsymbol{\varepsilon}_j(\mathbf{q})|^2}{\omega_j(\mathbf{q})} (1+n(\omega))\delta(\mathbf{Q}-\mathbf{q}-\boldsymbol{\tau})\delta(\omega-\omega_j(\mathbf{q}))$$

Can separately measure longitudinal and transverse modes



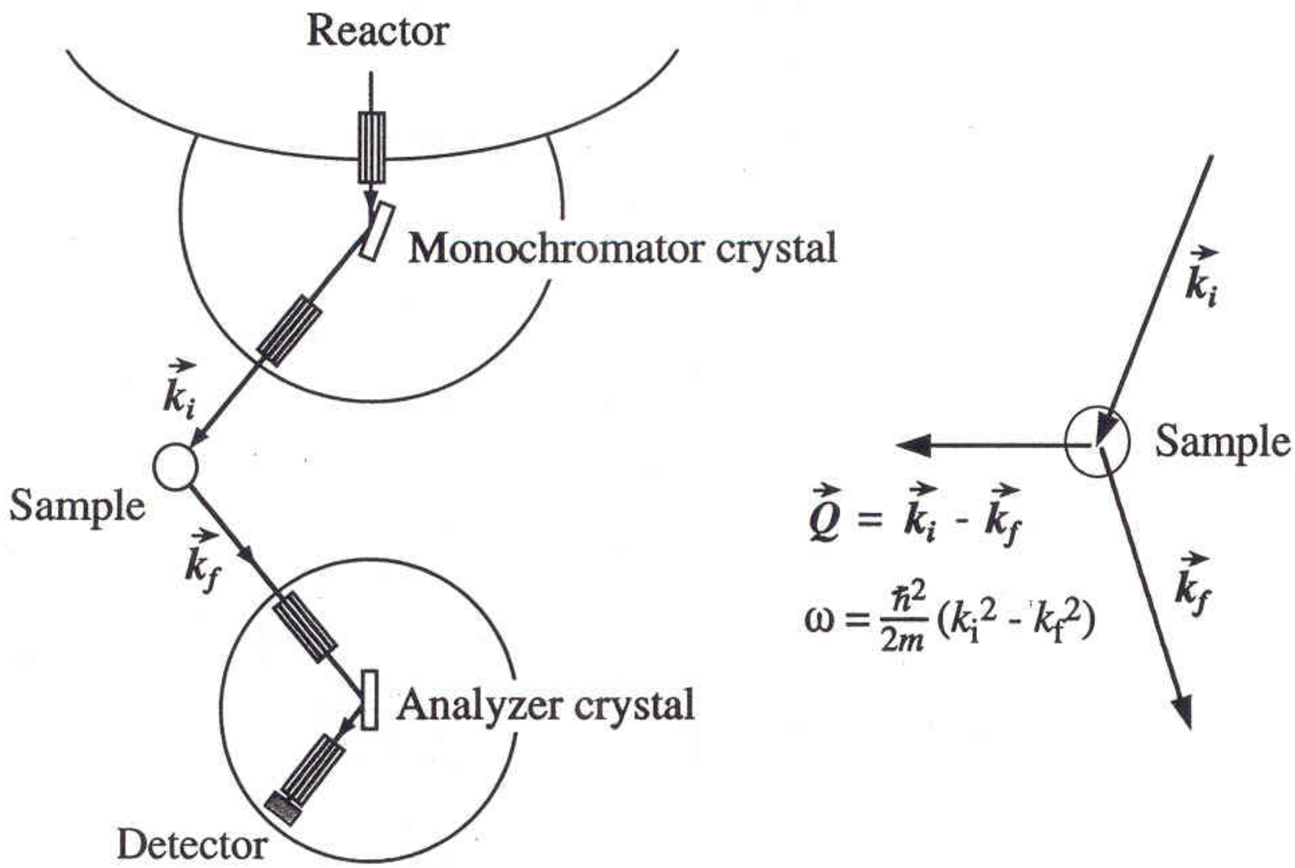
(Adapted from Bruce Gaulin, NXS 2011)

Example of a triple-axis spectrometer for inelastic scattering



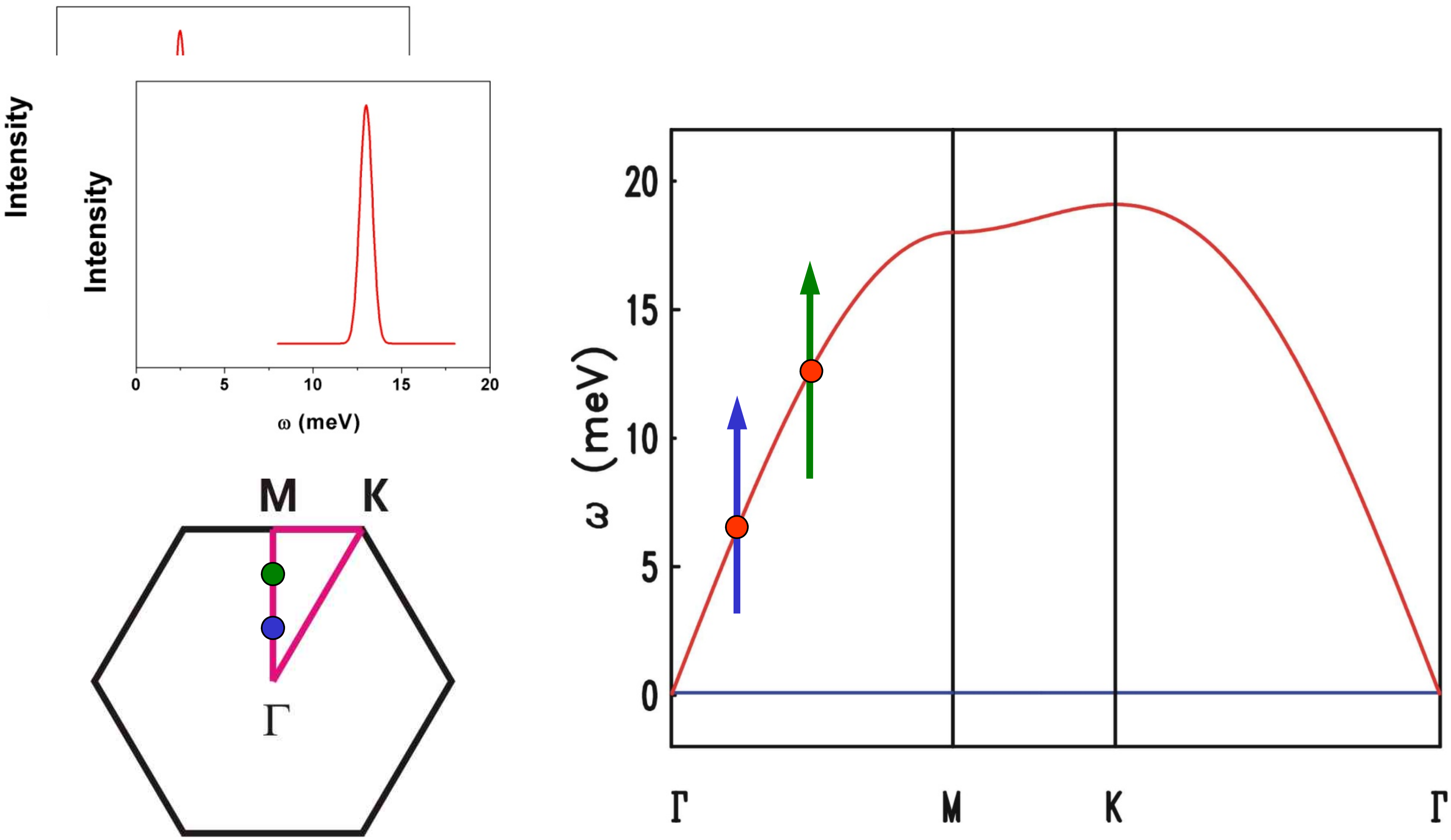
HB1 triple-axis spectrometer at the High Flux Isotope Reactor at Oak Ridge

Triple-axis neutron scattering technique

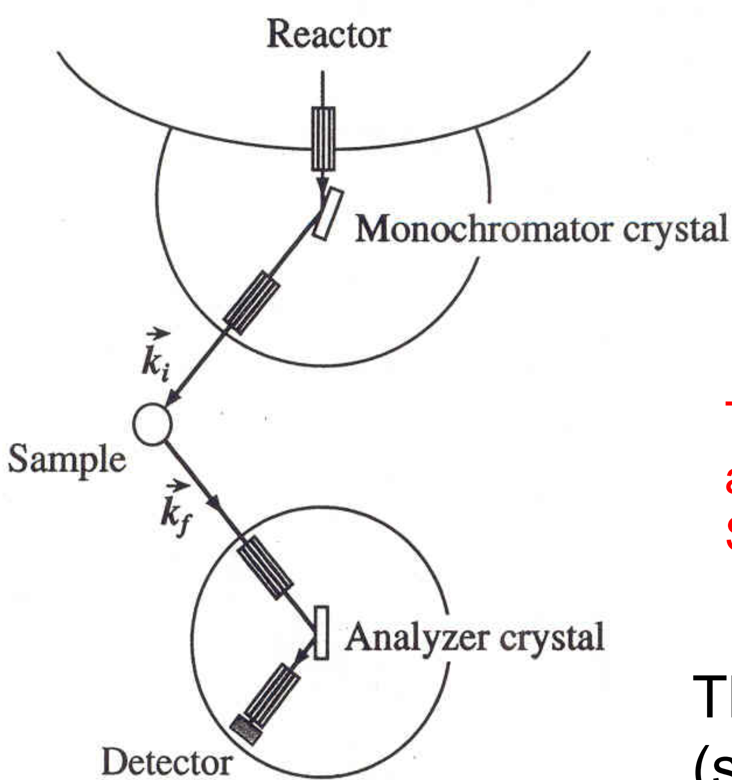


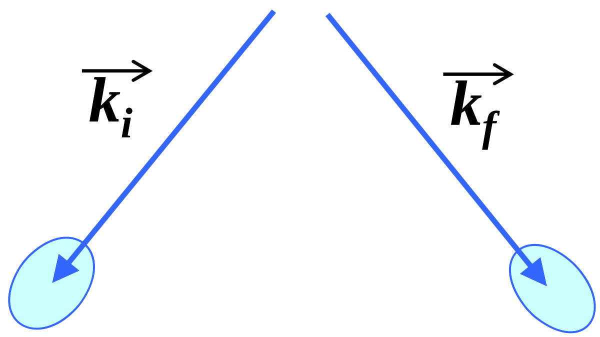
Monochromator/analyzer crystals typically pyrolytic graphite (PG).
Filters (also PG) are placed in beam to remove $\lambda/2$ neutrons.

Using neutrons to measure a dispersion surface



The triple-axis measurement concept is straightforward, however, for any experiment, we must understand the resolution of the instrument.



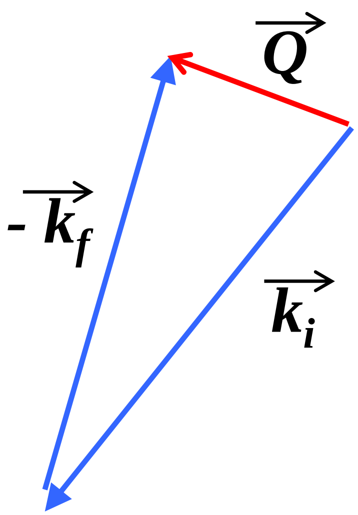


The neutrons in the incident beam have a spread in $\boldsymbol{k_i}$ (magnitude and direction). Same with the outgoing beam and $\boldsymbol{k_f}$.

The instrumental resolution function (spread in $\boldsymbol{Q}$ and ω) is an **ellipsoid**

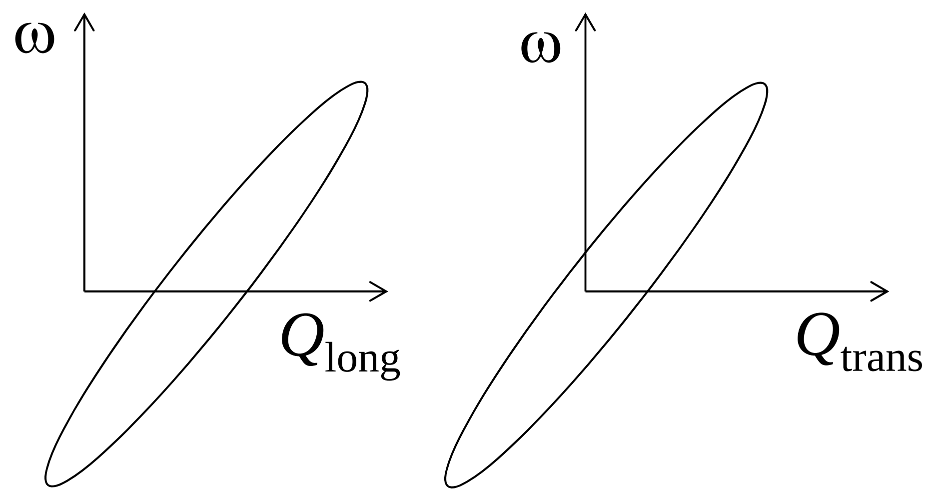
A little more on the resolution function

Consider 14.7 meV (2.67 A^{-1}) incident neutrons, and scattering process with Q ~ 1 A^{-1} and ω ~ 1 meV. A depiction of the scattering triangle is below.



Fact: the resolution ellipsoid is tilted in ($\boldsymbol{Q}$,ω) space

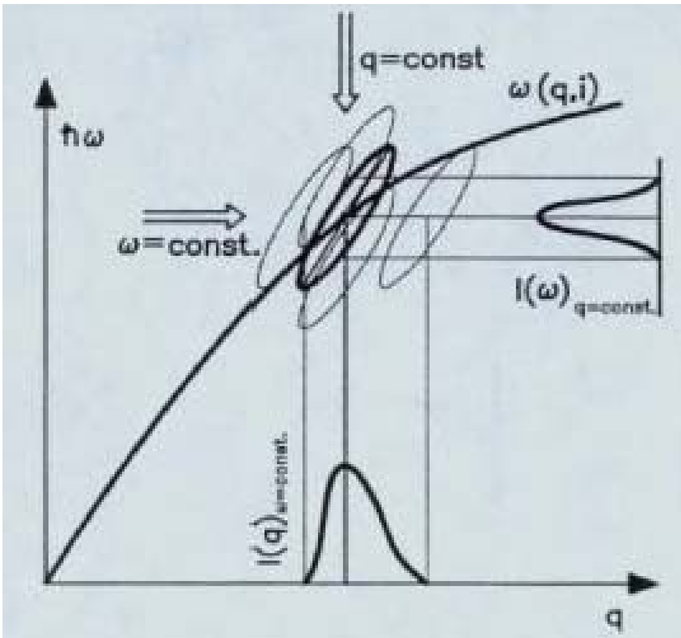
Question: which of the following is more correct?



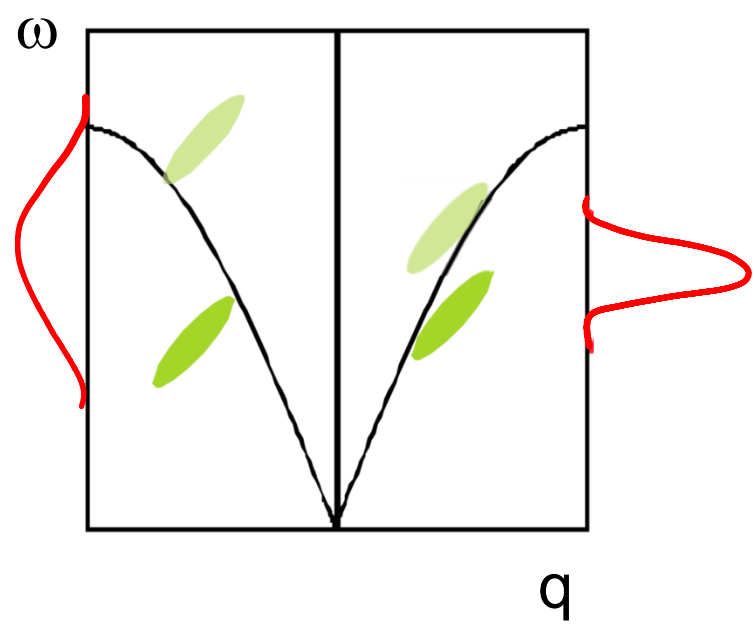
Answer: the one on the right. A spread in the <u>magnitude</u> of $\boldsymbol{k_f}$ (or $\boldsymbol{k_i}$) mostly couples to the direction transverse to $\boldsymbol{Q}$.

Different ways to scan through the dispersion surface

constant-*Q* versus constant-ω



Resolution "focusing"

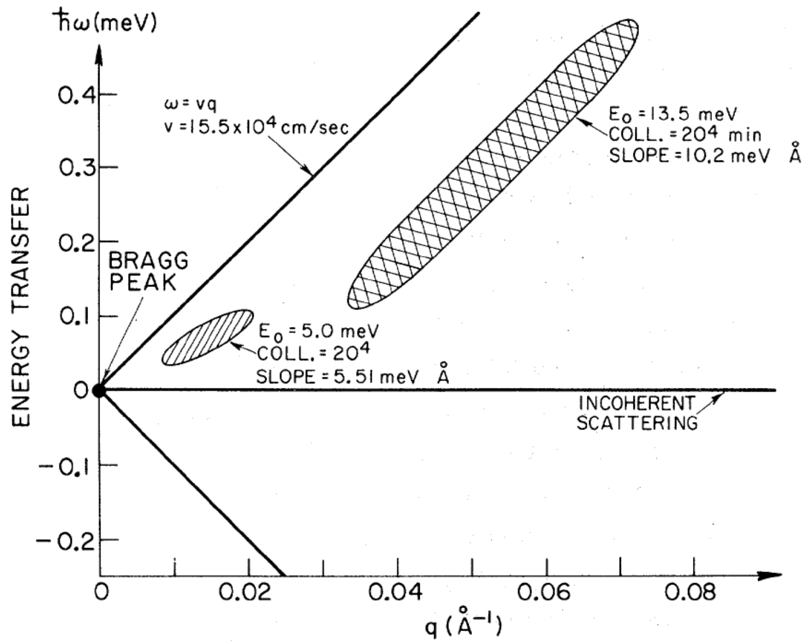


For a constant-***Q*** scan, the intrinsic ω-width (after deconvolving the resolution) is zero for harmonic phonons. For real phonons with a finite lifetime, we can introduce a finite width (say, using a damped oscillator model). The width in energy of the peak is proportional to the inverse-lifetime of the excitation.

Example: Phonon lineshapes in conventional superconductors

Shapiro, Shirane, and Axe studied phonons in superconducting niobium crystals with neutron scattering at energies below the SC gap.

Shapiro, et al, PRB 12, 4899 (1975)



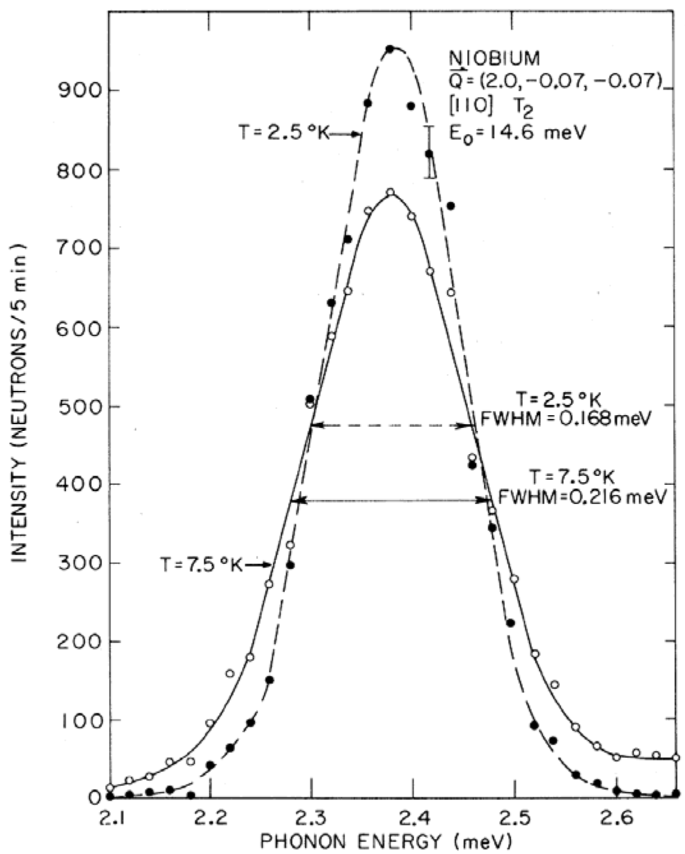
Question: below T_c, did the phonon peaks become

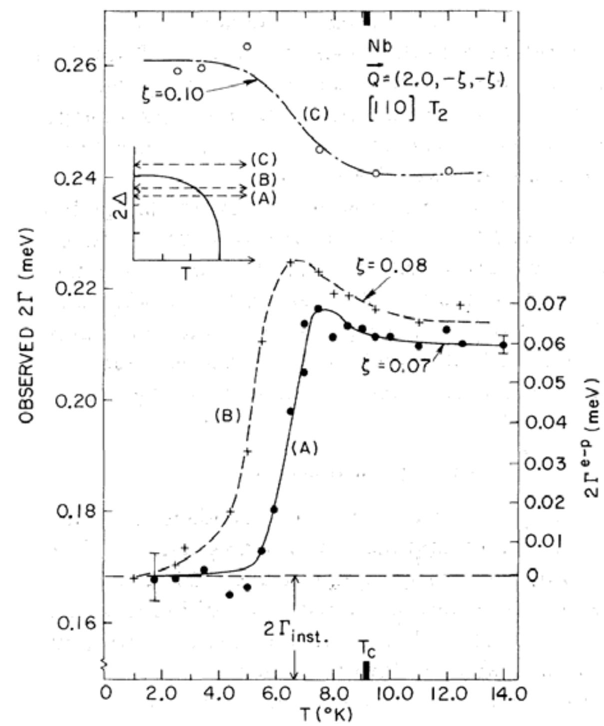
a) sharper or

b) broader?

Example: Phonon lineshapes in conventional superconductors

Shapiro, et al, PRB 12, 4899 (1975)





The linewidth decreased below T_C (life-time increased), due to removal of decay channels with the metallic electrons which are gapped out.

Magnetic order and excitations

The ferromagnetic and antiferromagnetic ground states typically break a continuous symmetry (ie. Heisenberg and XY models).

The low energy excited states are referred to as "spin waves" and the quantum of excitation is a "magnon."

Goldstone's Theorem (1963):

The energy of very long-wavelength spin waves vanishes.

"Whenever the original Lagrangian has a continuous symmetry group, the new solutions have a reduced symmetry and contain massless bosons."

"The massless particles … correspond to spin-wave excitation in which only the direction of the [phase angle] makes infinitesmal oscillations"

Simple case: the Heisenberg ferromagnet

$$H = -\sum_{ij} J(\vec{R}_i - \vec{R}_j)\,\vec{S}_i \cdot \vec{S}_j - g u_B H \sum_i S_i^z$$

Here, the exchange parameter $J(\boldsymbol{R}_i\text{-}\boldsymbol{R}_j)$ is positive and may, in principle, couple spins beyond nearest neighbors.

By writing the Hamiltonian using raising and lower operators,

$$\vec{S}_i \cdot \vec{S}_j = S_i^z S_j^z + S_i^+ S_j^-$$

it is clear that the fully aligned state $\uparrow\uparrow\uparrow\uparrow$

is the ***exact ground state*** (a good quantum eigenstate).

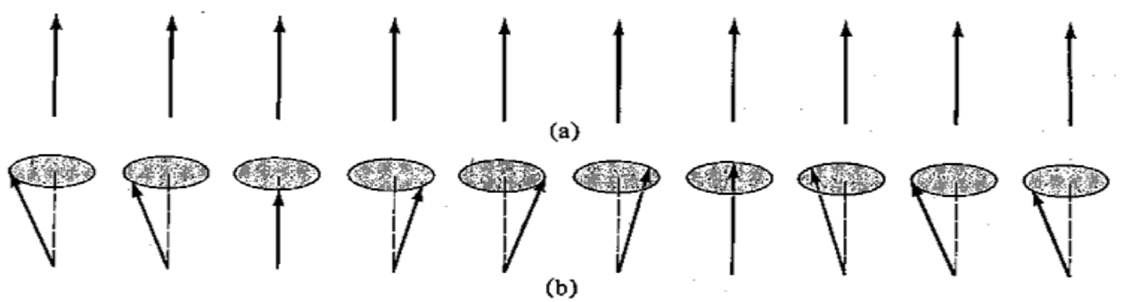
Simple case: the Heisenberg ferromagnet (cont'd)

The ground state has total spin NS.

The lowest energy excited states have total spin (NS-1).

For S=1/2, this may be thought of as having a single flipped spin, which is shared by the ensemble of spins.

These low energy excitations are spin waves.
Classical picture:



Note: the energy $\hbar\omega$ of the excitation depends on the wavelength $\boldsymbol{q}$.

Simple case: the Heisenberg ferromagnet (cont'd)

One can calculate the dispersion relation $\omega(\boldsymbol{q})$ using *linear spin wave theory* (as seen in Lovesey, chapter 9). (A convenient method is to use a Holstein-Primakoff transformation of the spin operators to independent boson operators.)

Result: $\omega(\vec{q}) = g\mu_B H + 2S\left(\mathcal{J}(0) - \mathcal{J}(\vec{q})\right)$

where $\mathcal{J}(\vec{q}) = \sum_{\vec{R}} J(\vec{R})\, e^{-i\vec{q}\cdot\vec{R}}$

For interactions between nearest neighbors only:

$$\omega(\vec{q}) = g\mu_B H + 2zJS\left(1 - \gamma(\vec{q})\right)$$

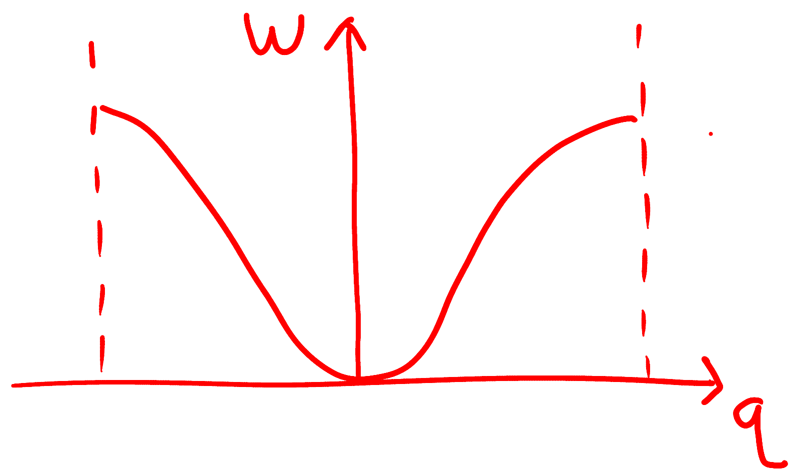
where $\gamma(\vec{q}) = \frac{1}{z}\sum_{\vec{\rho}} e^{i\vec{q}\cdot\vec{\rho}}$

Simple case: the Heisenberg ferromagnet (cont'd)

For cubic lattice (with lattice parameter a), the dispersion at small q is ***quadratic*** in q:

$$\omega(\boldsymbol{q}) \approx g\mu_B H + Dq^2$$

where $D = 2JSa^2$



How can we measure this with neutron scattering?

The one-magnon neutron scattering cross-section

We saw that the magnetic neutron scattering cross-section is related to the dynamic correlation function.

For spin waves, only the transverse terms in the correlation function (ie., $\langle S_i^+ S_j^-(t) \rangle$ and $\langle S_i^- S_j^+(t) \rangle$) give rise to inelastic scattering.

Result:

$$\frac{d^2\sigma}{d\Omega\, dE'} = r_0^2 \frac{k'}{k} \frac{(2\pi)^3}{V_0} \frac{S}{2} \left(1+\hat{Q}_z^2\right) \left\{\frac{g}{2} F(\vec{Q})\right\}^2 e^{-2W(\vec{Q})}$$

$$\sum_{\vec{\tau},\vec{q}} \Big\{ \delta(\hbar\omega(\vec{q})-\hbar\omega)\, \delta(\vec{Q}-\vec{q}-\vec{\tau})\, (n(\omega(\vec{q}))+1) + \delta(\hbar\omega(\vec{q})+\hbar\omega)\, \delta(\vec{Q}+\vec{q}-\vec{\tau})\, n(\omega(\vec{q}))$$

First term in sum corresponds to magnon creation and second term corresponds to magnon annihilation.

Pop quiz:

1) You measure an inelastic peak in several Brilliouin zones at the same reduced ***q*** (note, the ***Q*** wavevector is not the same). You notice the intensity of the peak decreases rapidly as ***Q*** gets larger.

You can conclude:

a) the peak is likely due to a spin-wave

b) the peak is likely due to a phonon

a) is correct

recall: the phonon peak intensity grows at Q^2

The one-magnon neutron scattering cross-section

A few more notes about the one-magnon cross-section:

1) Roughly the same magnitude as inelastic scattering from phonons.
   Also, takes similar form as sharp surfaces of dispersion.

2) Depends on the form factor of the magnetic ion as $F^2(\boldsymbol{Q})$
   which falls off with increasing *Q*.
   Useful: can distinguish between excitations from spin waves and phonons (whose cross-section increases with *Q*) by measurements in multiple Brillouin zones out to large *Q*.

3) Depends on the orientation factor $(1+\hat{Q}_z^2)$ where $\hat{Q} = \dfrac{\vec{Q}}{|\vec{Q}|}$

   This arises from the form of the neutron interaction with the spin.
   Note, z is chosen to be the quantization axis of the spin (which may be aligned using an applied field for the FM case).
   For the Heisenberg FM, the spin waves are transverse modes which are 2-fold degenerate. Useful.

JOURNAL OF APPLIED PHYSICS VOLUME 39, NUMBER 2 1 FEBRUARY 1968

Spin Waves in 3*d* Metals*

G. SHIRANE, V. J. MINKIEWICZ, AND R. NATHANS
Brookhaven National Laboratory, Upton, New York

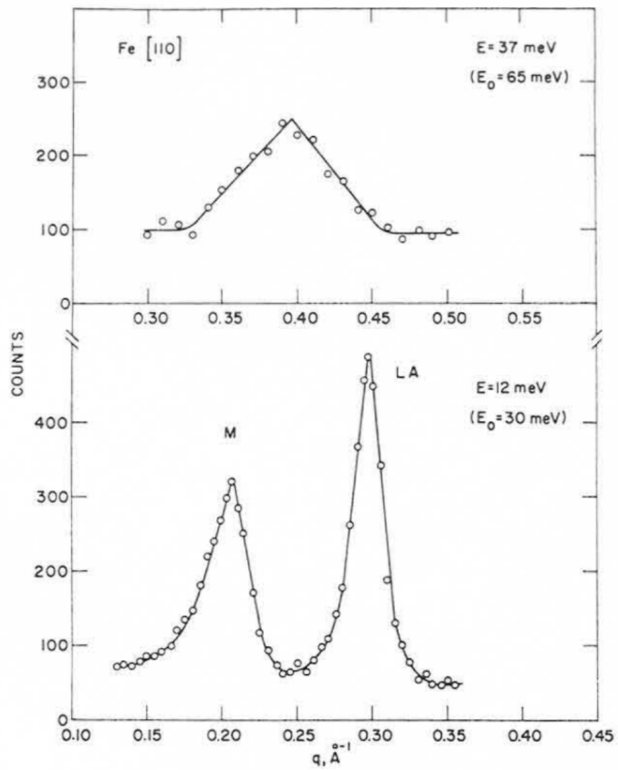


FIG. 2. Contant E scans of spin waves (M) and longitudinal acoustic (LA) phonons in Fe at 295°K with fixed incoming energy E_0.

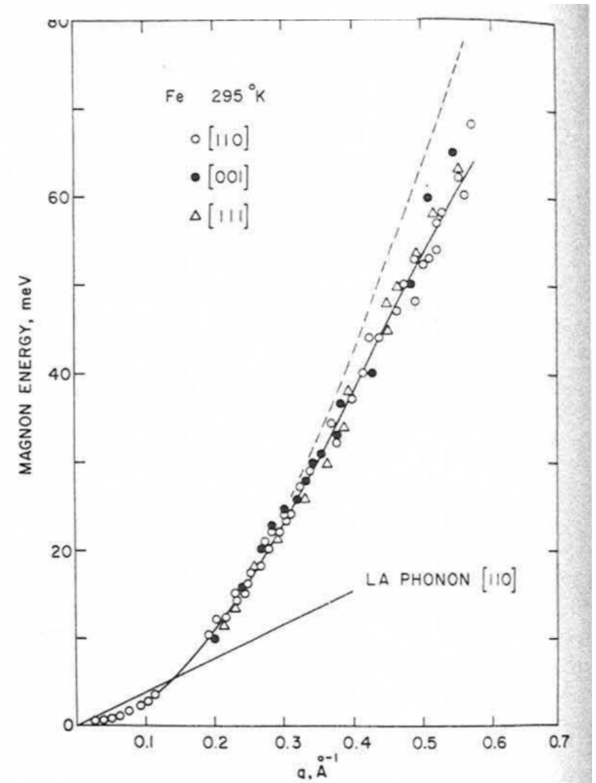


FIG. 4. Dispersion relation for Fe at 295°K. The broken line corresponds to the Heisenberg model with $D=281$ meV Å^2.

Triple-axis spectroscopy on single crystals

- quadratic dispersion (FM in iron)
- overlap with acoustic phonons

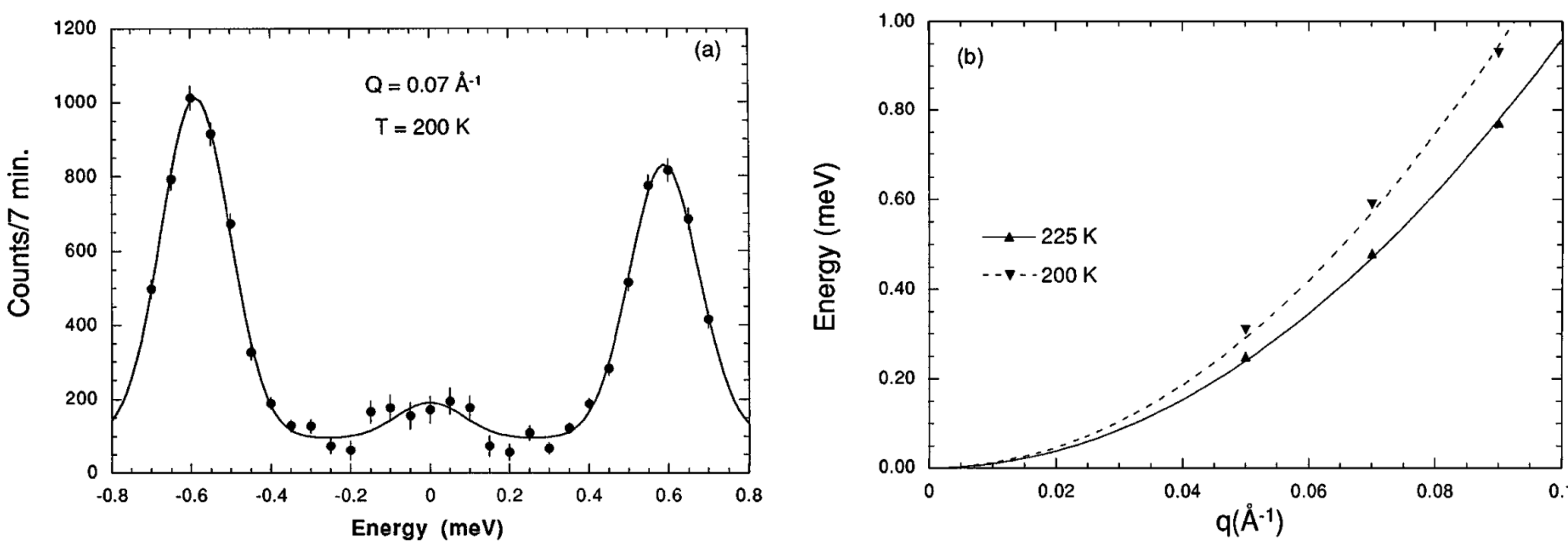
Using powder samples to extract the small q dispersion

VOLUME 76, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1996

Unconventional Ferromagnetic Transition in $La_{1-x}Ca_xMnO_3$

J. W. Lynn,* R. W. Erwin, J. A. Borchers, Q. Huang,* and A. Santoro
Reactor Radiation Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

J-L. Peng and Z. Y. Li
Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742
(Received 1 February 1996)



Measurements at small q near (0,0,0) yield *D.*

Requirements:

1) A <u>ferromagnet</u> on a <u>cubic lattice</u>

2) Good energy- and Q- resolution

Next “simple” case:
the nearest neighbor Heisenberg antiferromagnet

$$H = J\sum_{<ij>} \vec{S}_i \cdot \vec{S}_j$$

Here, *J* is positive and the expected ***classical ground state***

is $\uparrow\downarrow\uparrow\downarrow$ also called the ***Néel state***.

Again, by writing the Hamiltonian using:

$$\vec{S}_i \cdot \vec{S}_j = S_i^z S_j^z + S_i^+ S_j^-$$

it is clear that the Néel state $\uparrow\downarrow\uparrow\downarrow$

is ***<u>not</u>*** a quantum eigenstate.

Next “simple” case:
the nearest neighbor Heisenberg antiferromagnet

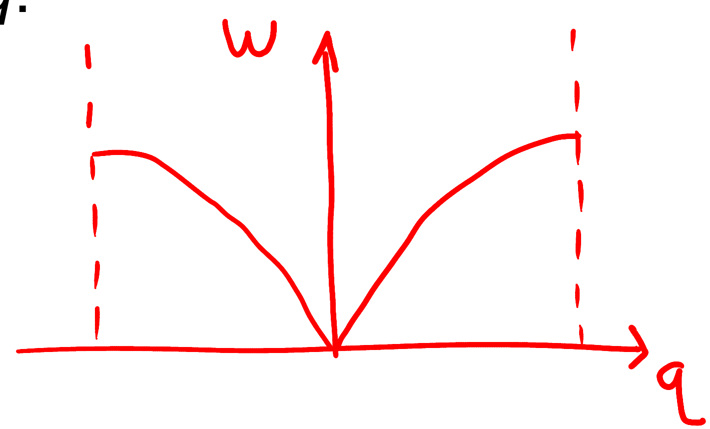
Let’s use the Néel state as an approximate ground state consisting of two sublattices (one with spin-up and one with spin-down).

Again, calculate the dispersion using linear spin wave theory.

Result: $\hbar\omega(\vec{q}) = 2zJS\sqrt{1-\gamma^2(\vec{q})}$

For a simple cubic lattice (with lattice parameter *a*), the dispersion at small *q* is ***linear*** in *q*:

$\hbar\omega(\vec{q}) \approx 4\sqrt{3}\,JSa\,q$



Time-of-flight methods

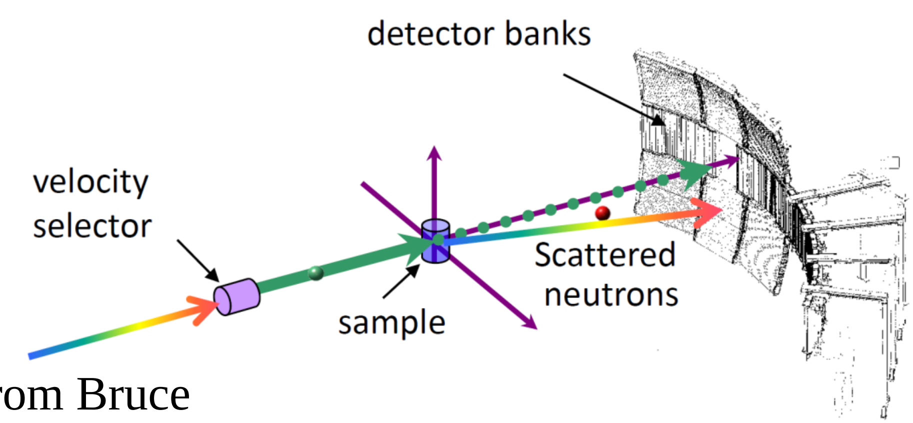
Spallation neutron source

Pharos – Lujan Center

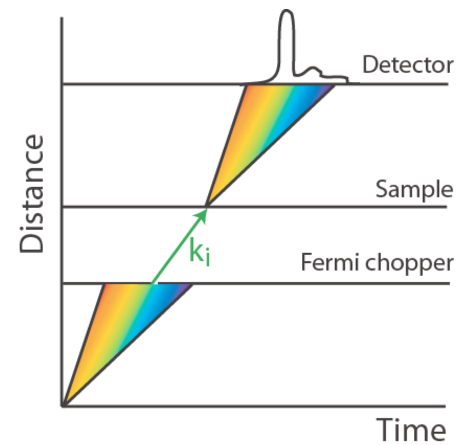
v (m/msec) = 3.96 / λ (A)

- Effectively utilizes time structure of pulsed neutron groups

$$t = \frac{d}{v} = \left(\frac{m}{h} d\right)\lambda$$



(adapted from Bruce Gaulin, NXS 2011)



We can measure a neutron's wavelength by measuring its **speed**.
Can get resolutions of 1-5% of E_i.

Planning an experiment:
Time-of-flight versus triple-axis

Time-of-flight advantages:

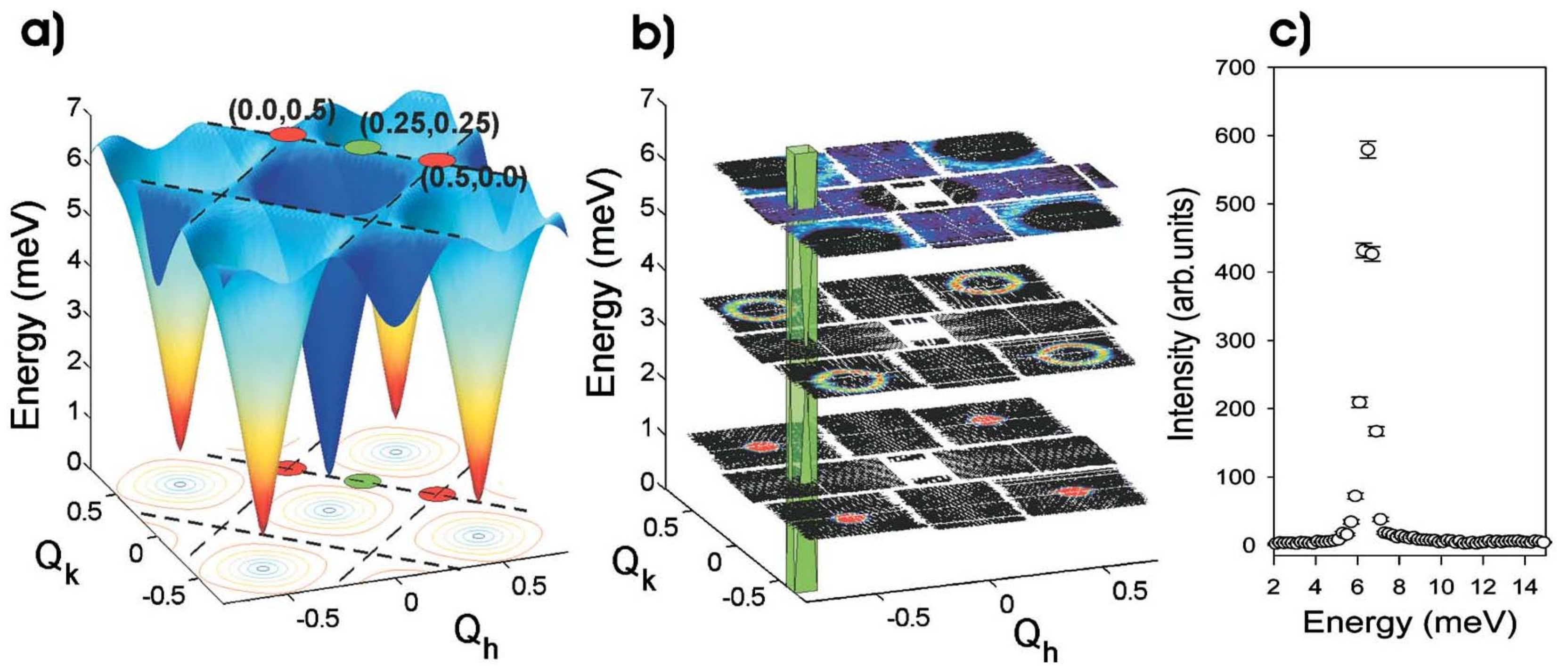
1) Large detector banks give efficient collection of data in a broad swath of ($\boldsymbol{Q}$,ω) space.
   - excellent for measuring dispersions throughout multiple Brilliouin zones
2) Spallation sources are better at producing higher energy neutrons (>100 meV) compared to reactors

Triple-axis advantages:

1) Extremely flexible
   - can tailor resolution function with choice of energy, collimations, monochromator crystals,…
2) Excellent for focused studies of specific ($\boldsymbol{Q}$,ω) coordinates
3) Polarized beam readily accessible

Neutron scattering from spin waves in the
S=5/2 square-lattice Heisenberg antiferromagnet Rb_2MnF_4

T. Huberman et al, PRB **72**, 014413 (2005)



Measured using a time-of-flight technique on
the MAPS spectrometer (ISIS, UK)

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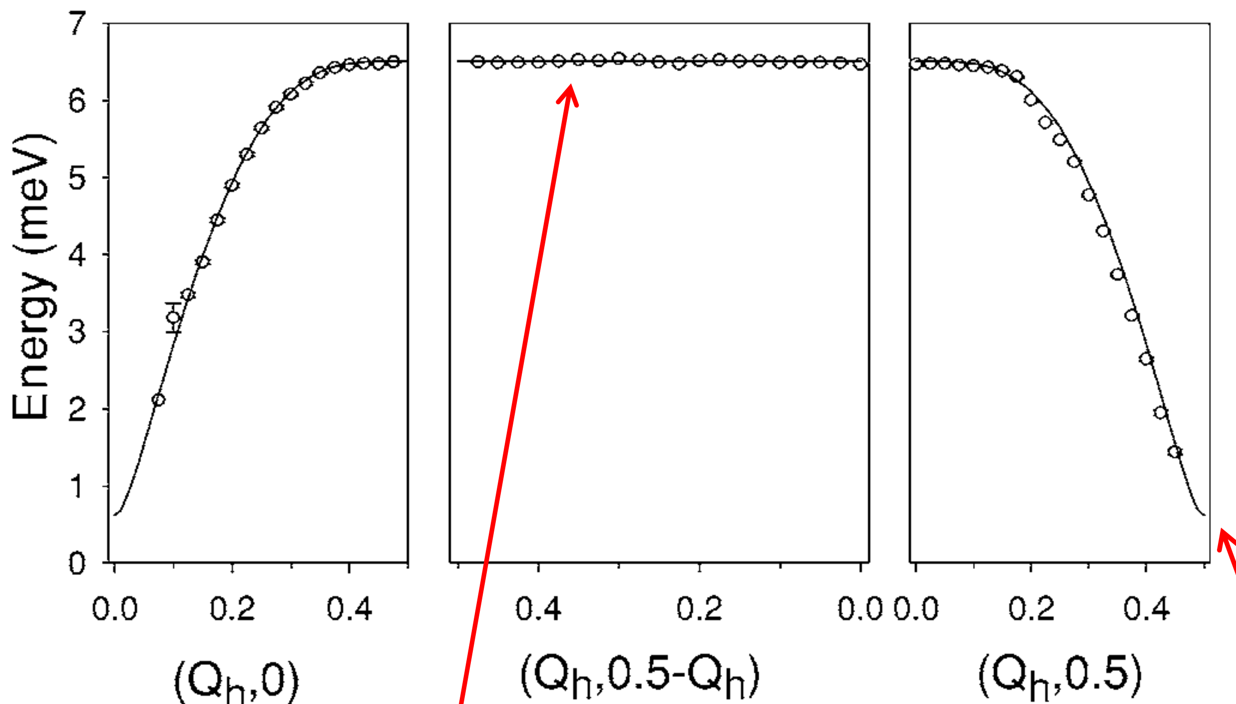


No dispersion along zone boundary (if only NN exchange)

Small gap at zone center due to Ising-like anisotropy

$$\hat{H} = J \sum_{\langle ii' \rangle} [S_i^x S_{i'}^x + S_i^y S_{i'}^y + (1+\delta_z) S_i^z S_{i'}^z]$$

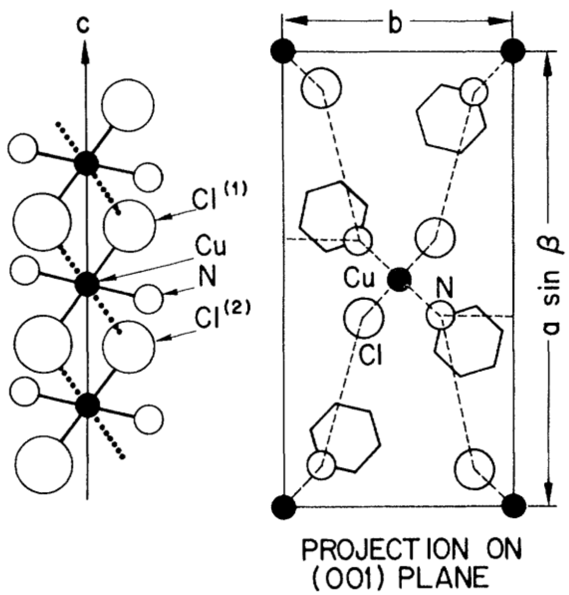
Neutron scattering and S=1/2 spin chain

VOLUME 32, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 1974

Dynamics of an $S=\frac{1}{2}$, One-Dimensional Heisenberg Antiferromagnet

Y. Endoh* and G. Shirane , et al.

"CPC"



$$\mathcal{H} = 2J \sum_i \vec{S}_i \cdot \vec{S}_{i+1}, \quad S = \tfrac{1}{2},$$

with $J = 13.4$ K.

1-dim has the advantage of being relatively simple for calculations.
 - J can be accurately determined by comparing Susceptibilty with Bonner-Fisher model

Also, the dispersion relation of the low energy excitations was calculated by des Cloizeaux &Pearson (Phys. Rev. **128**, 2131 (1962)):

$$\boxed{\varepsilon(q) = \pi J |\sin(qc)|}$$

In contrast with: $\varepsilon(q) = 2J|\sin(qc)|$ for classical spin waves

Neutron scattering and S=1/2 spin chain

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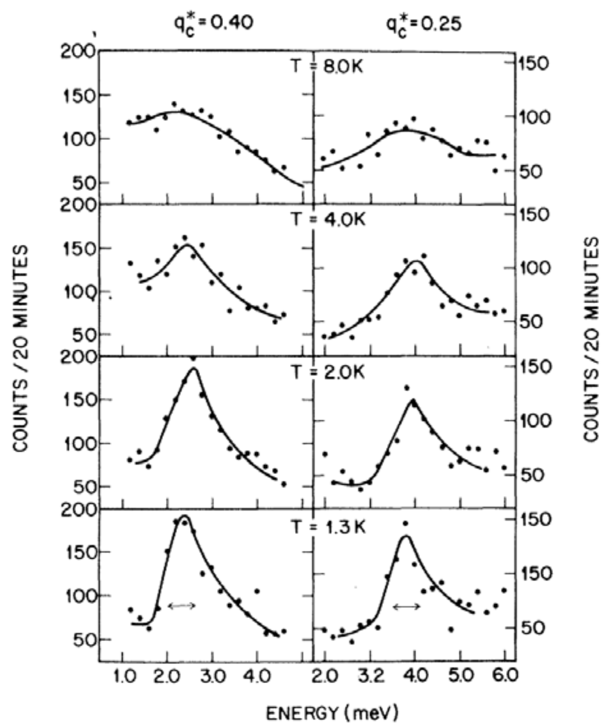
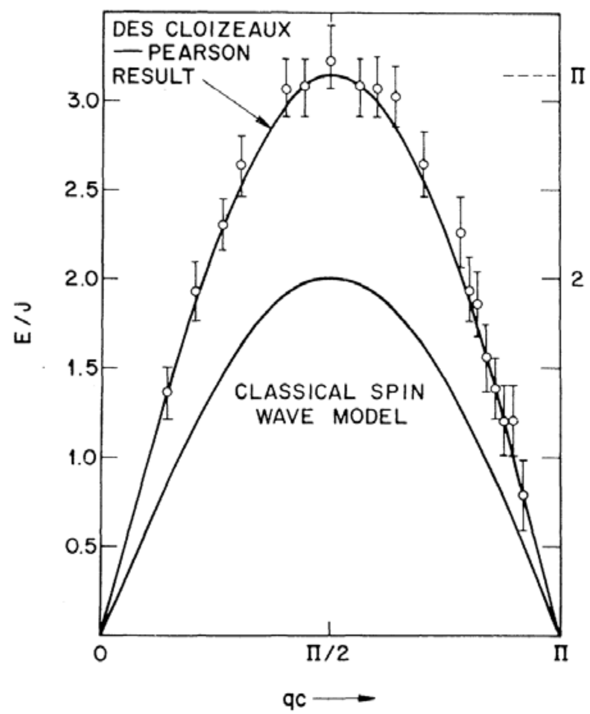




A recurring theme in the early days:
synergy between theory and neutron experiments

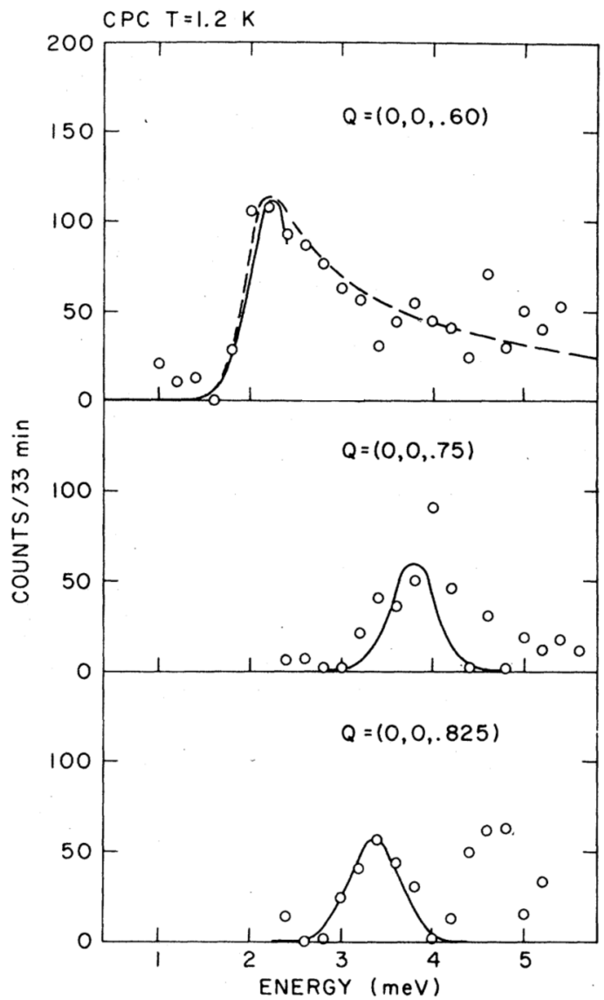
Question at the time: are these spin-wave excitations?

Neutron scattering and S=1/2 spin chain

PHYSICAL REVIEW B VOLUME 18, NUMBER 7 1 OCTOBER 1978

Neutron study of the line-shape and field dependence of magnetic excitations in $CuCl_2 \cdot 2N(C_5D_5)$

I. U. Heilmann and G. Shirane, et al.



Magnetic scattering

<u>Question:</u>
The asymmetry of the inelastic scatttering is:
1) an instrumental artifact--a resolution effect
2) real, indicating new physics

<u>Answer:</u> It is real physics

Neutron scattering and S=1/2 spin chain

PHYSICAL REVIEW B VOLUME 18, NUMBER 7 1 OCTOBER 1978

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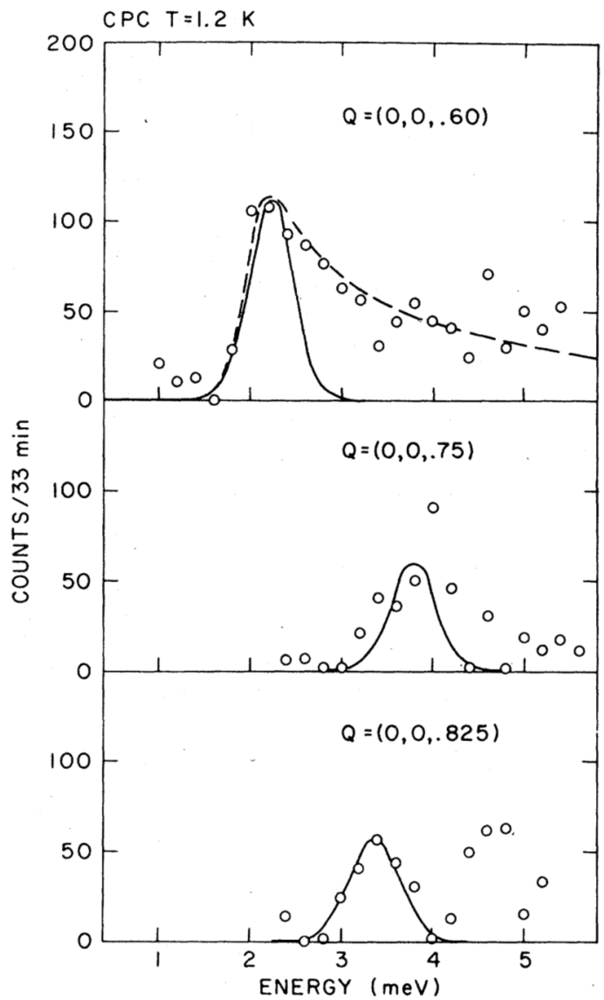
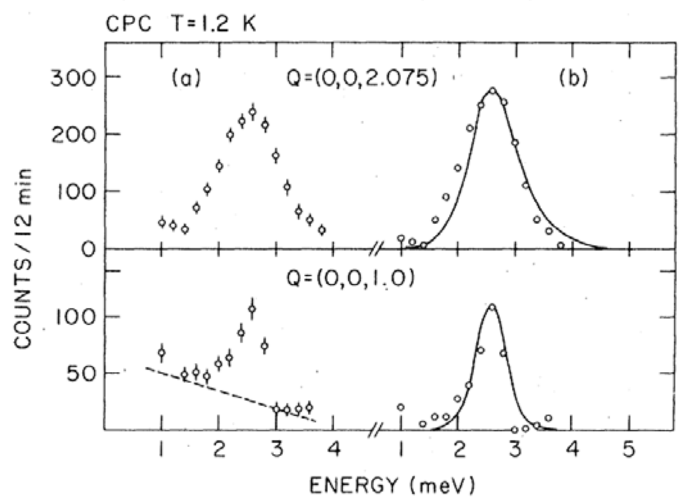


Magnetic scattering

Phonon scattering



The asymmetry in the magnetic scattering is real.
→ the magnetic peaks are not due to spin-waves
(it's a sharp lower bound to a continuum scattering)

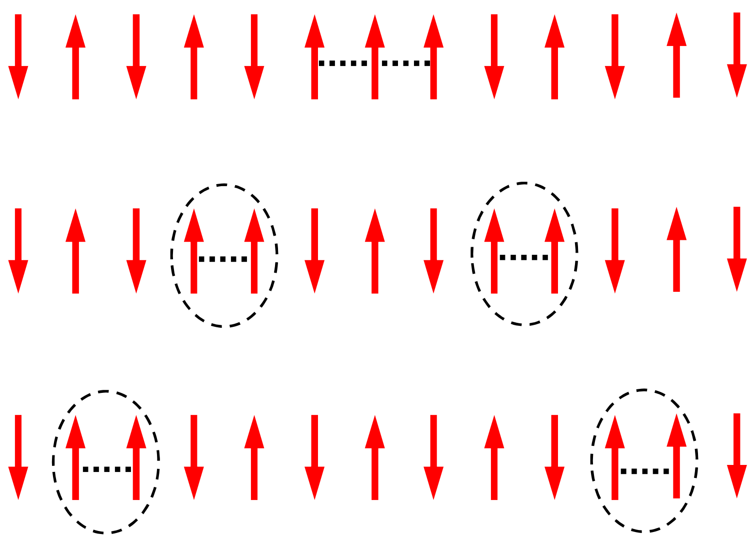
The quantum spin liquid in <u>one-dimension</u>

For S=1/2 antiferromagnetic (AF) Heisenberg chain

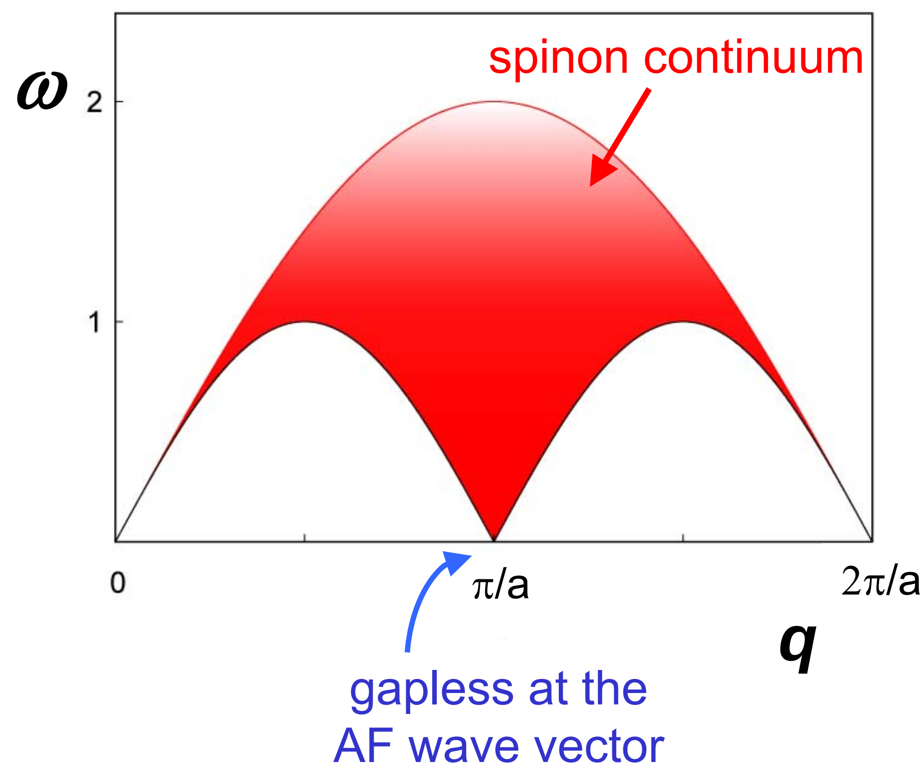
No long-range Néel order, even at T=0 K! (H. Bethe, 1931)

<u>Ground state</u>: superposition of singlets, short-range AF order

An S=1 excitation breaks up into two S=1/2 *<u>spinons</u>*



Spin excitation spectrum



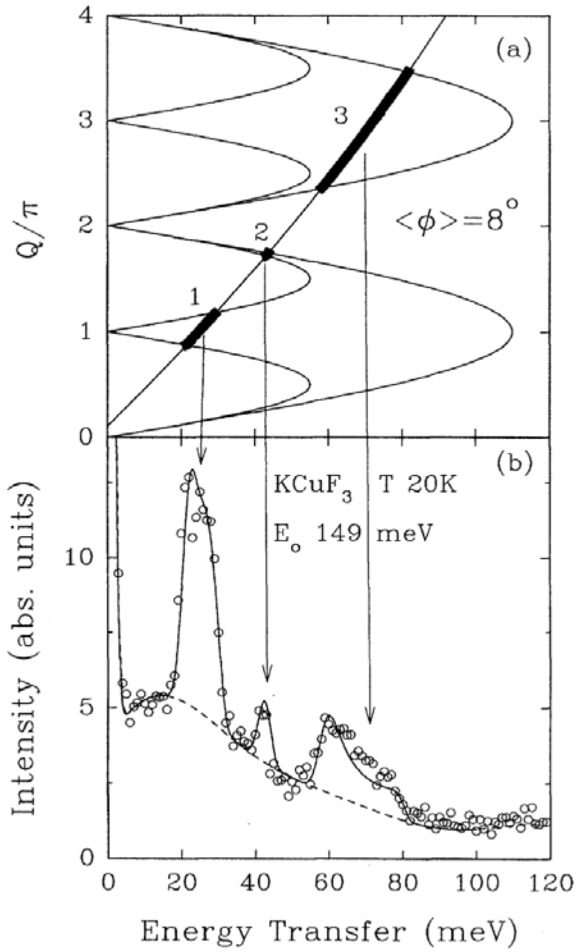
The excitations are novel: ***<u>spinons</u>*** (not spin-waves).

Neutron scattering and S=1/2 spin chain

PHYSICAL REVIEW B VOLUME 52, NUMBER 18 1 NOVEMBER 1995-II

Measurement of the spin-excitation continuum in one-dimensional $KCuF_3$ using neutron scattering

D. Alan Tennant and Roger A. Cowley, et al.



Using time-of-flight techniques:

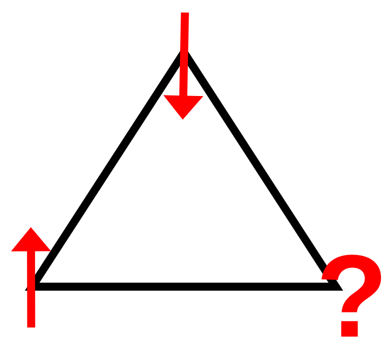
Clear observations of a continuum of spinon excitations.

Has well-defined lower and upper bounds.

Case study: A novel spin wave mode due to geometrical frustration on the kagome lattice

The main ingredient for geometrical frustration:

Lattices based on triangles



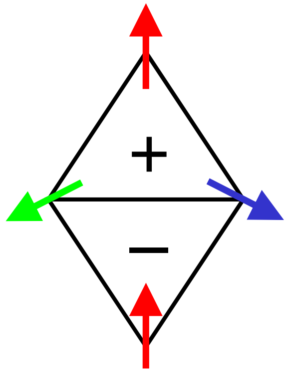
$$H = J \sum_{<ij>} \vec{S}_i \cdot \vec{S}_j$$

$J > 0$ (antiferromagnetic)

A few more basics:

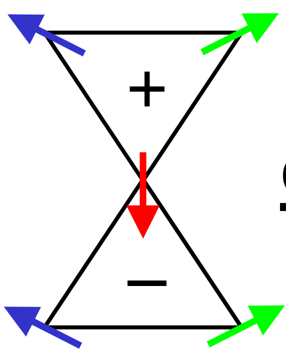
120° arrangement of spins on each triangle minimizes energy

Edge sharing

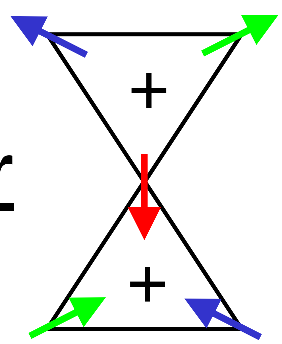


One triangle constrains entire lattice

Corner sharing



or

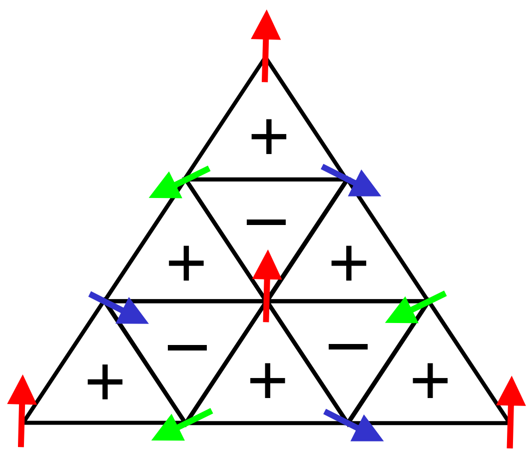


Higher degree of degeneracy

Broken symmetries in ordered state:

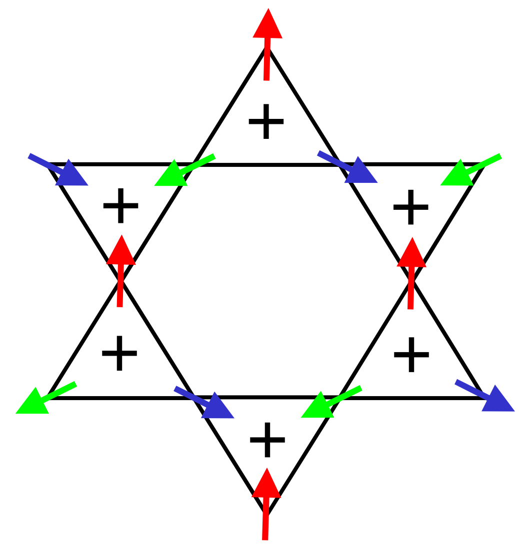
1) Spin rotation
2) Chirality $\vec{K} = \frac{2}{3\sqrt{3}}(\vec{S}_1 \times \vec{S}_2 + \vec{S}_2 \times \vec{S}_3 + \vec{S}_3 \times \vec{S}_1)$

Triangular



Must have staggered chirality

Kagomé



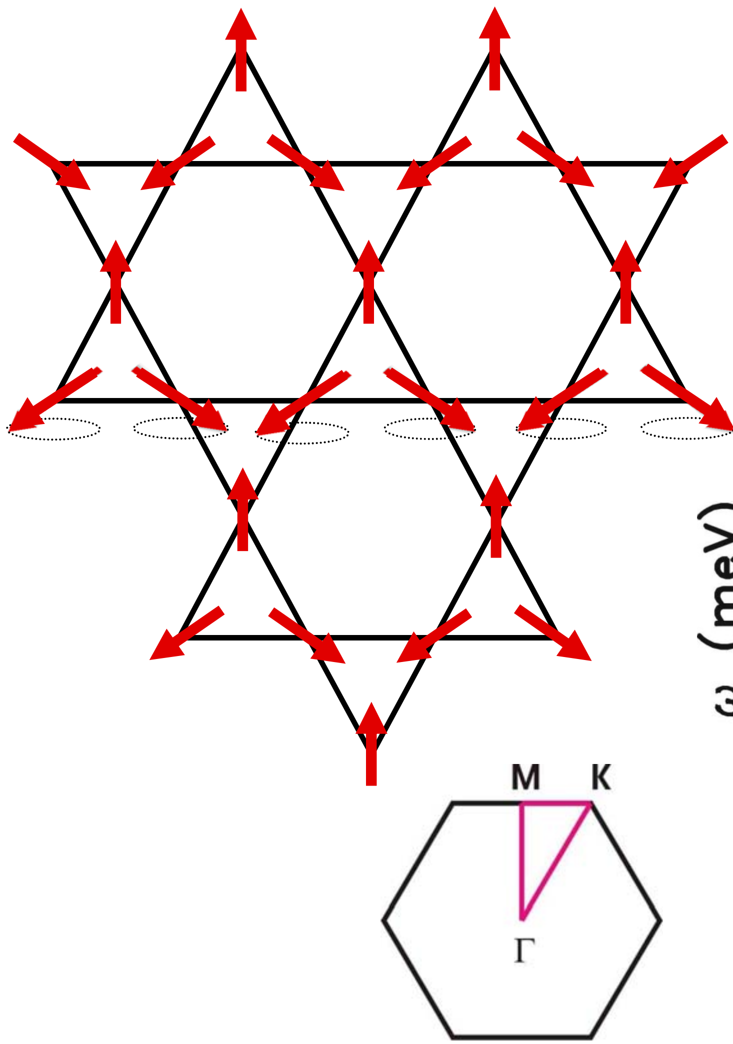
Many chiral patterns. One possible state: "$\boldsymbol{Q}$ = 0"

Example: spin-waves for classical spins on kagomé

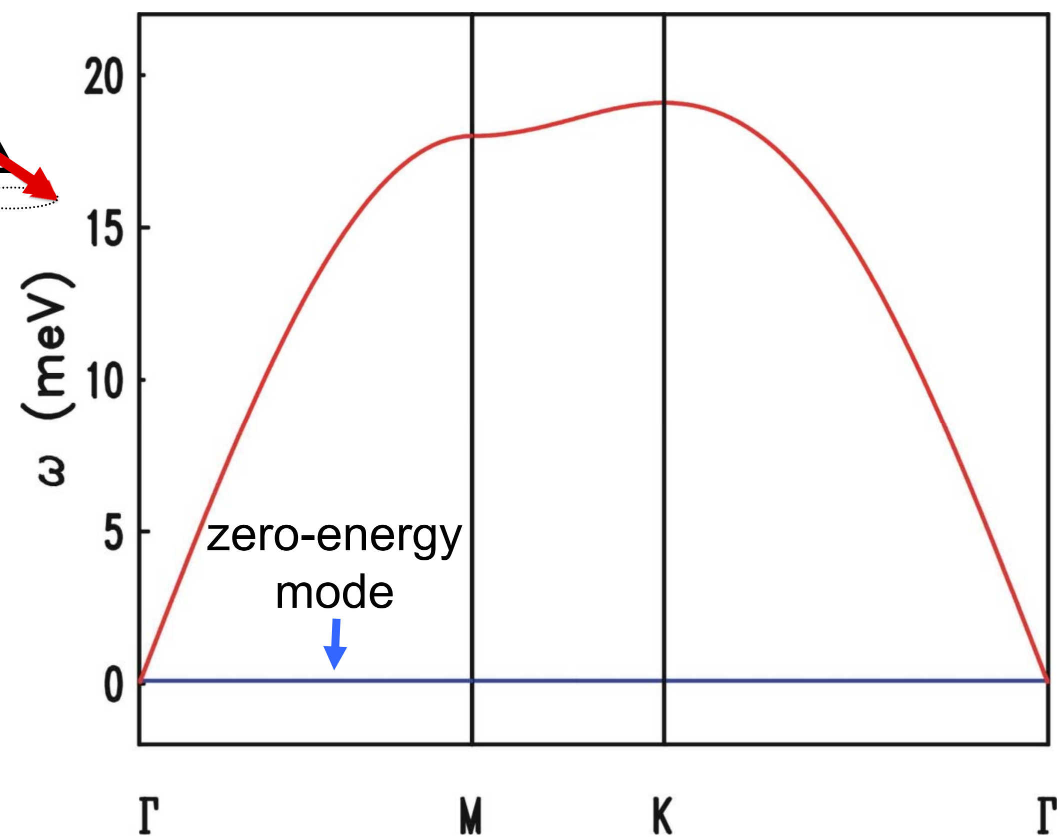
$$H = J\sum_{<ij>} \vec{S}_i \cdot \vec{S}_j$$

Excitations usually disperse:
$E \propto q$ for antiferromagnet

Due to frustrated geometry, a <u>dispersionless mode</u> exists



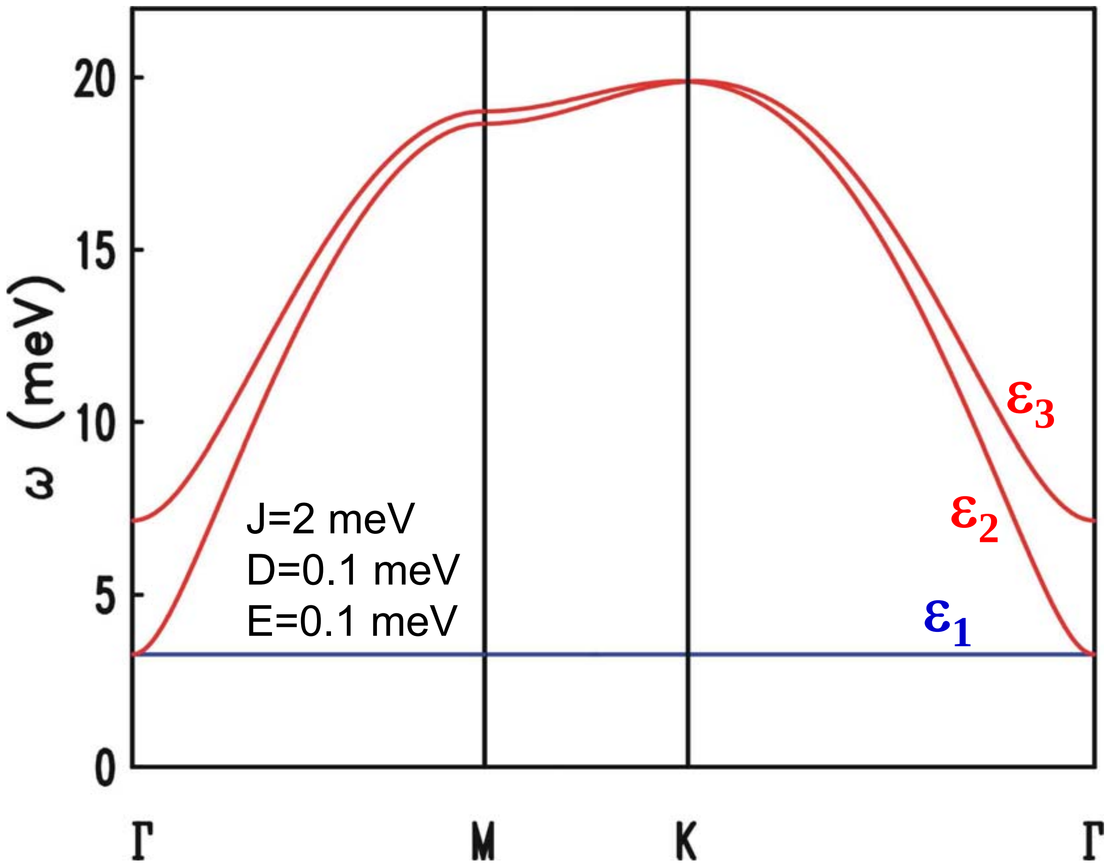
Harris, Kallin, Berlinsky, PRB **45**, 2899 (1992)

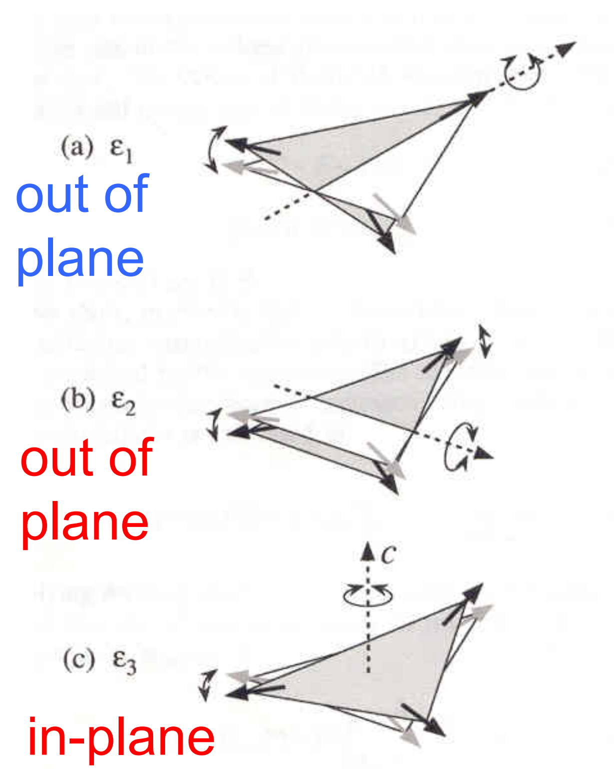


For real materials, add spin-anisotropy:

$$H = J \sum_{<ij>} S_i \cdot S_j + D_{XY} \sum_i \left(S_i^z\right)^2 - E_{Ising} \sum_i \left[\left(S_i^{x'}\right)^2 - \left(S_i^{y'}\right)^2\right]$$

Model calculation with test parameters:



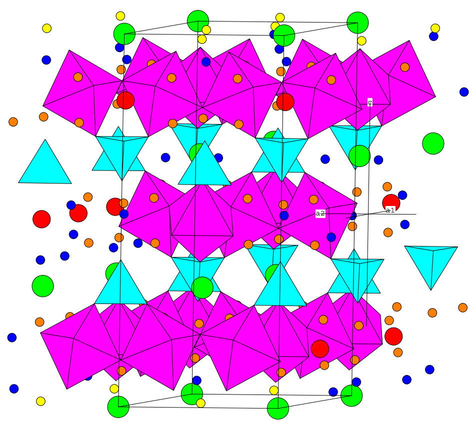


→ The zero-mode gets "lifted"

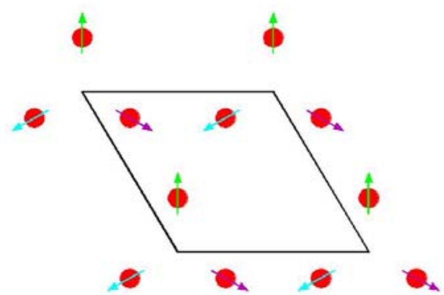
Studying crystals of the classical kagome antiferromagnet: iron jarosite $KFe_3(OH)_6(SO_4)_2$

D Grohol *et al,* Nature Materials 4, 323 (2005)

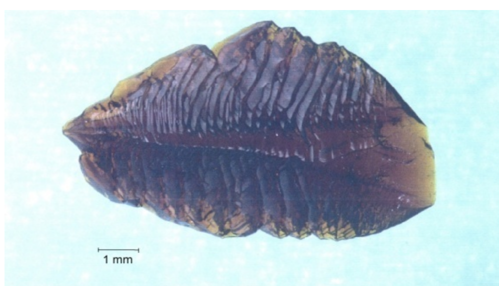
K Matan *et al,* PRL 96, 247201 (2006)



Fe^{3+} S=5/2



- Single, undistorted kagomé layers
- Stoichiometrically pure
- Crystals can be made

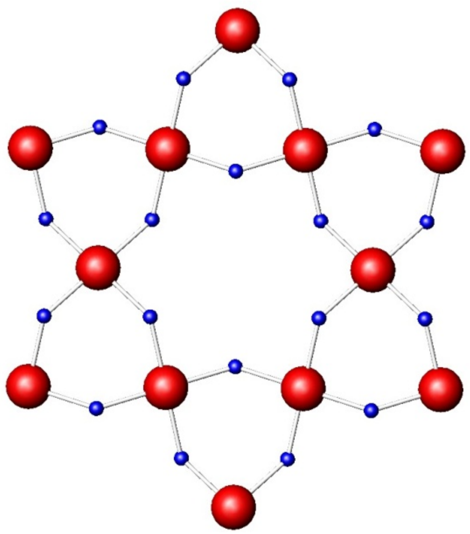


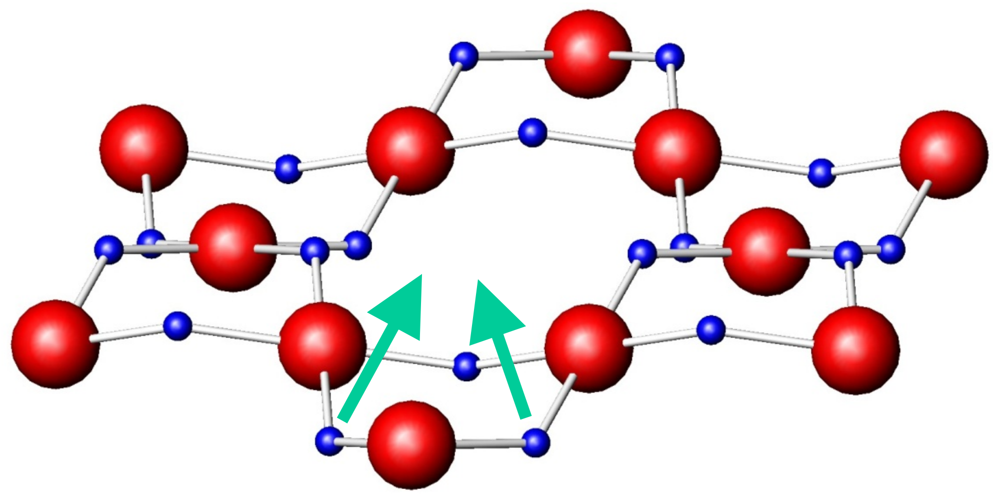
$$= \quad H = J \sum_{<ij>} \vec{S}_i \cdot \vec{S}_j \quad ?$$

The Dzyaloshinski–Moriya interaction

- dominant perturbation to Heisenberg Hamiltonian

$$H = \sum_{nn} J\, \vec{S}_i \cdot \vec{S}_j + \boxed{\vec{D} \cdot (\vec{S}_i \times \vec{S}_j)} + \sum_{nnn} J_2\, \vec{S}_i \cdot \vec{S}_j$$





$$\vec{D} = (0, D_y, D_z)$$

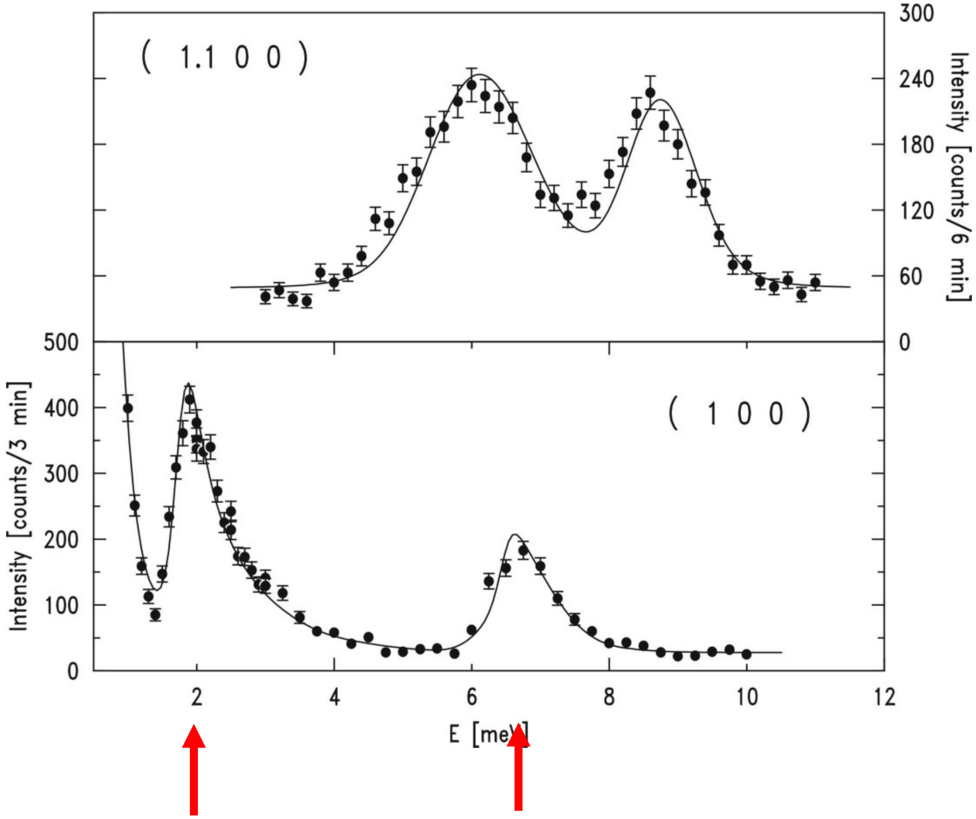
$\boldsymbol{D_z}$: gives *XY*-like anisotropy, selects chirality

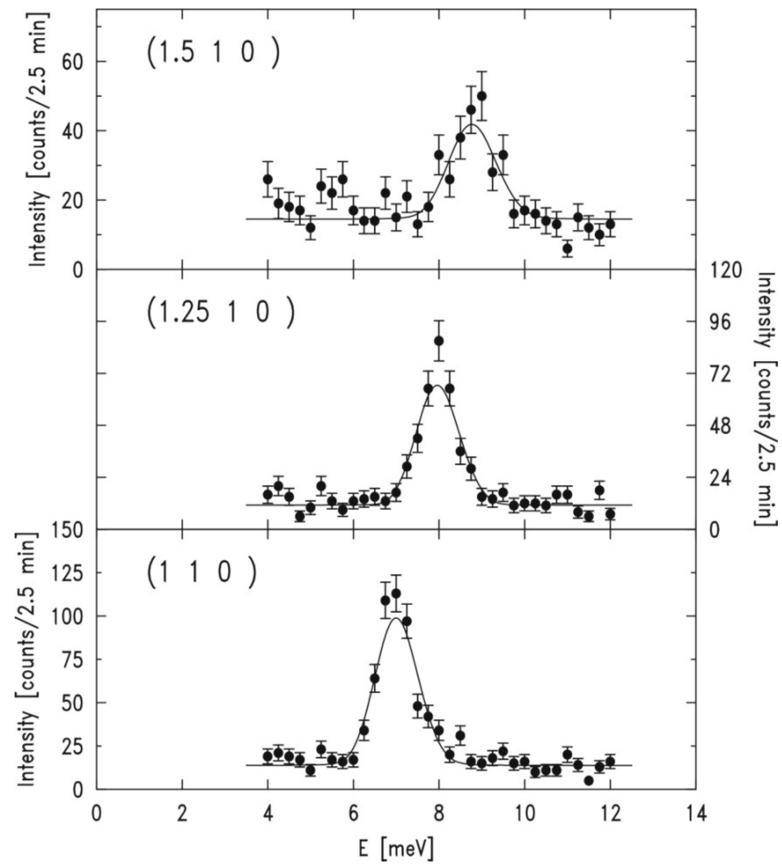
$\boldsymbol{D_y}$: gives Ising-like anisotropy, cants spins (weak FM)

Inelastic neutron scattering from spin wave modes

Constant-Q and constant-E scans taken on HB1 at HFIR

4 parameters (J, J_2 & D_z, D_y components) determine all peak positions

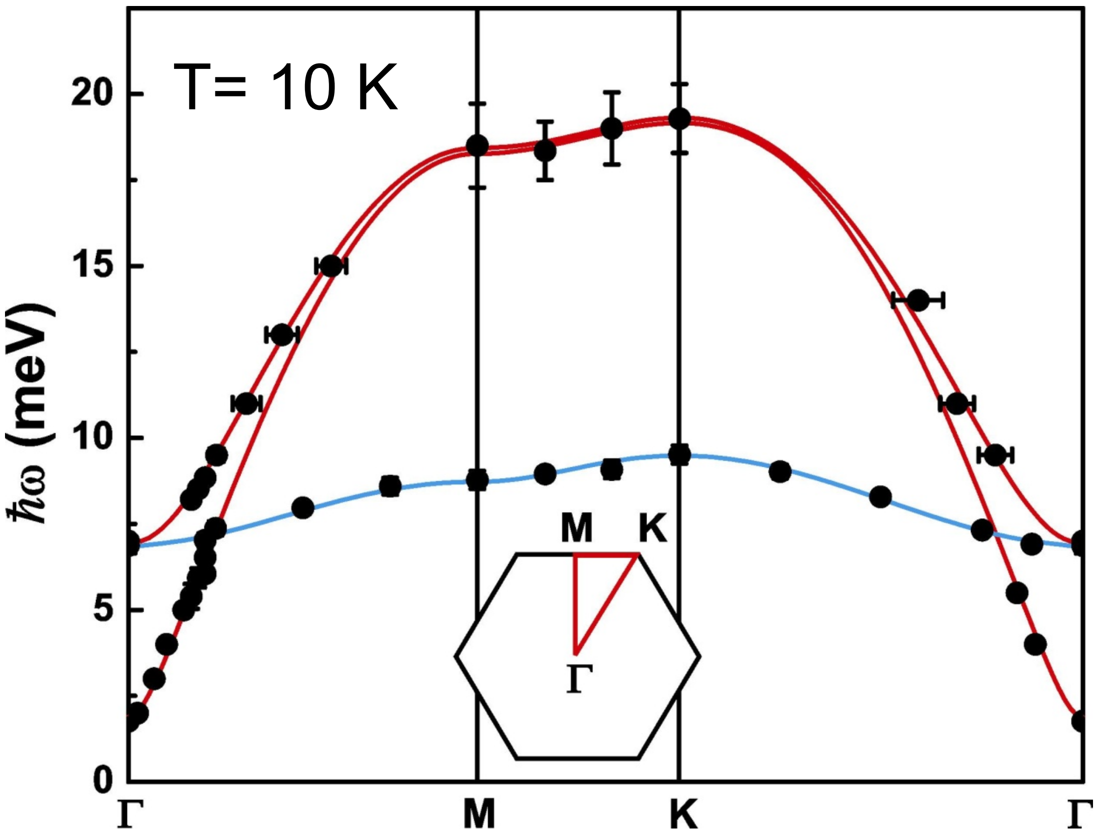




Gaps at zone center

Novel “dispersionless” mode

Spin waves in iron jarosite (S=5/2 kagomé lattice)



K Matan, YL, *et al.*, PRL 96, 247201 (2006)

J = 3.18 (4) meV

J_2 = 0.11 (1) meV

D_z = -0.196 (4) meV

$|D_y|$ = 0.197 (2) meV

(Dzyaloshinski-Moriya int.)

1) "Flat" dispersion of a mode indicative of a localized excitation (here, due to frustration)

Other local excitations: Ising magnet, crystal fields, rattler modes

verified with a momentum-resolved probe

Question: can spinons exist in a two-dimensional antiferromagnet?

The lynchpin experiment:

Inelastic neutron scattering on **single crystals**

(find spinons in a 2D kagome magnet !)

Obstacles for this experiment:

1) Small spin value S=1/2
2) No sharp peaks expected in ω or $\boldsymbol{Q}$
3) No recipe for crystals

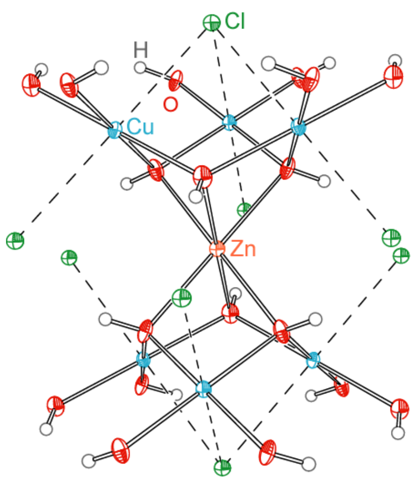
An ideal S=1/2 kagomé lattice material

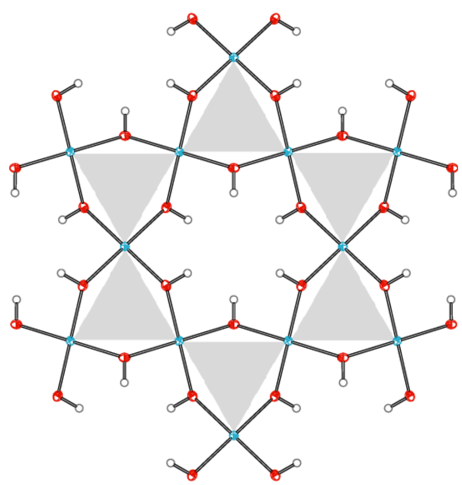
<u>Herbertsmithite</u> ($ZnCu_3(OH)_6Cl_2$)

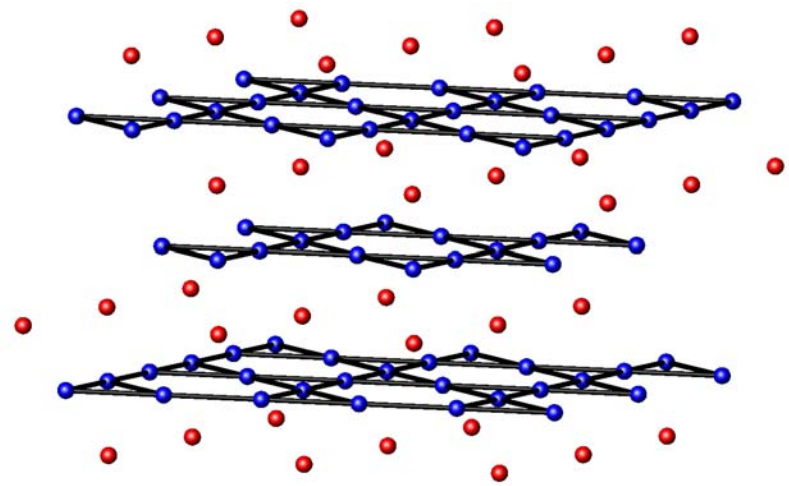
S=1/2 Cu^{2+} kagomé layers separated by non-magnetic Zn^{2+} layers

Shores *et al.*, J. Am. Chem. Soc. **127**, 13 462 (2005)

Helton *et al*, Phys. Rev. Lett., **98**, 107204 (2007)





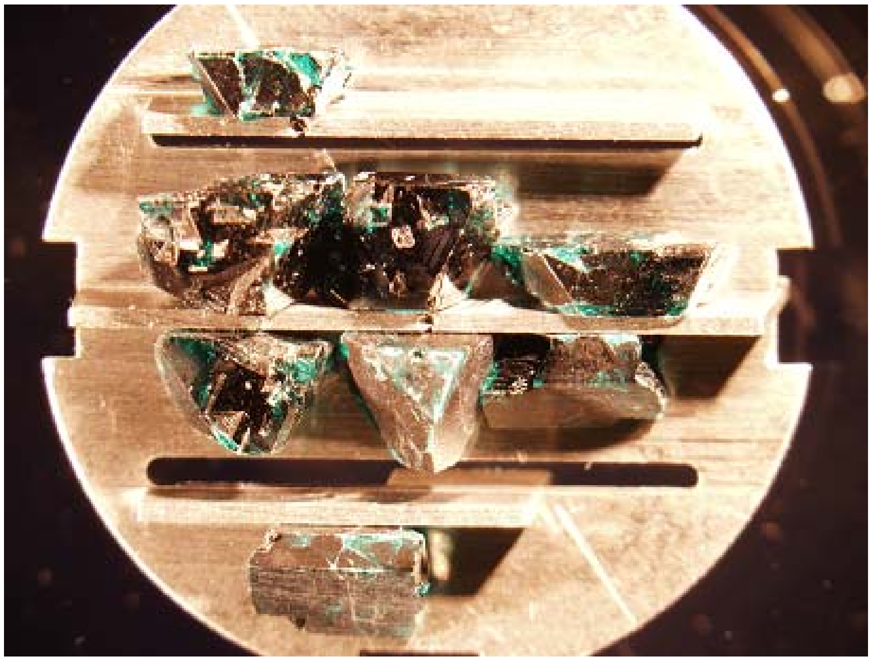


This has the ideal kagomé structure

The importance of single crystals for neutron scattering

Inventing and perfecting a new crystal growth method --the "hydrothermal zone"

T. H. Han *et al.*, PRB 83, 100402(R) (2011)

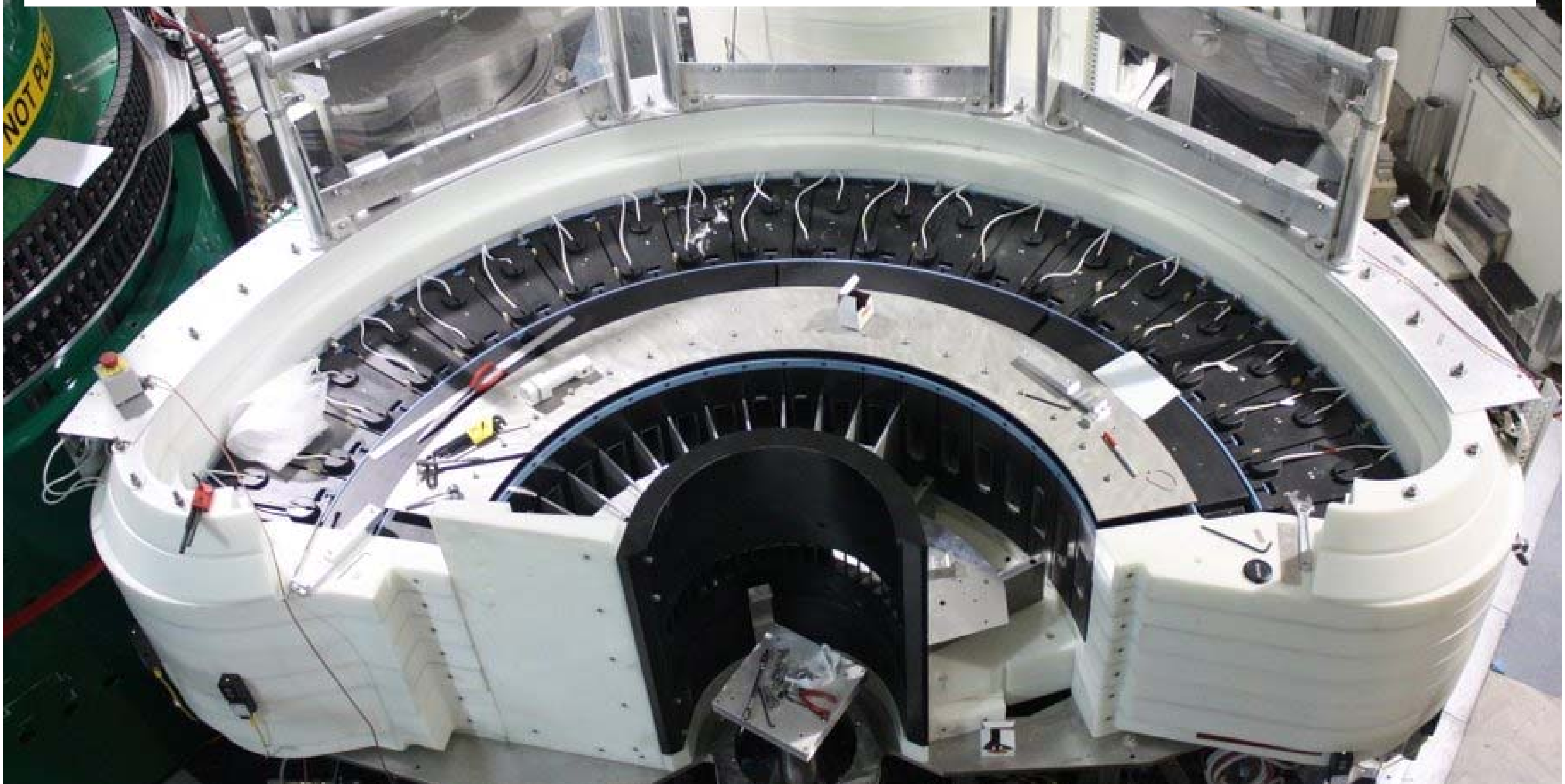


← 2cm →

All 15 crystals (1.25 g total mass) coaligned within 2 degrees
(the divergence of the neutron beam is ~1-2 degrees)

A powerful variation of the triple-axis technique:

New high-throughput multi-axis crystal spectrometer **MACS**
(at NIST Center for Neutron Research)



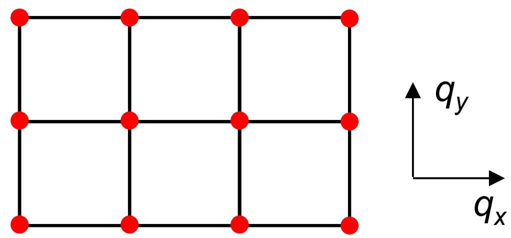
For measurements of spinons, low background is key

Expectations for the magnetic excitation spectrum

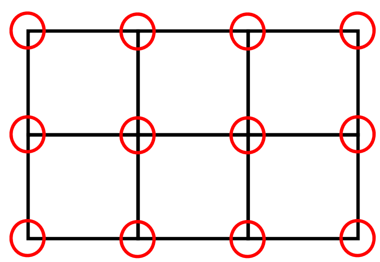
S=1/2 square lattice

ordinary spin-waves

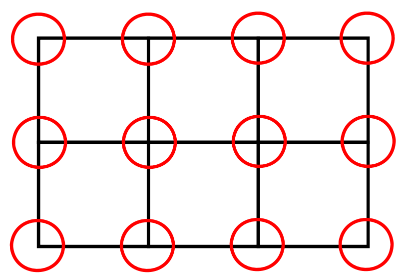
ω=0
slice



ω=J/5

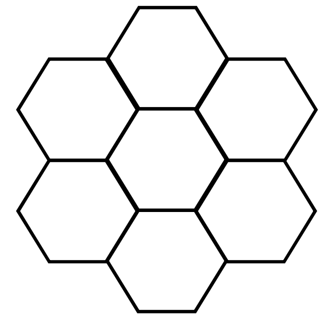


ω=J/2



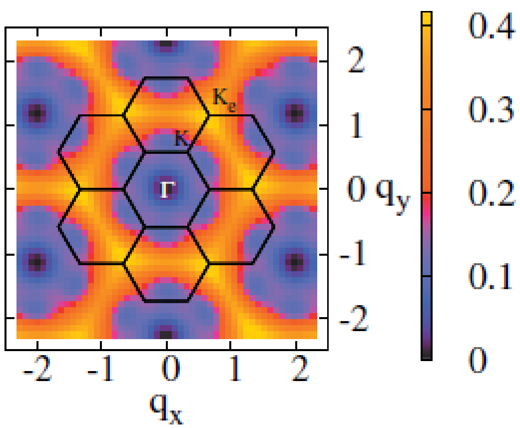
S=1/2 kagomé lattice

???



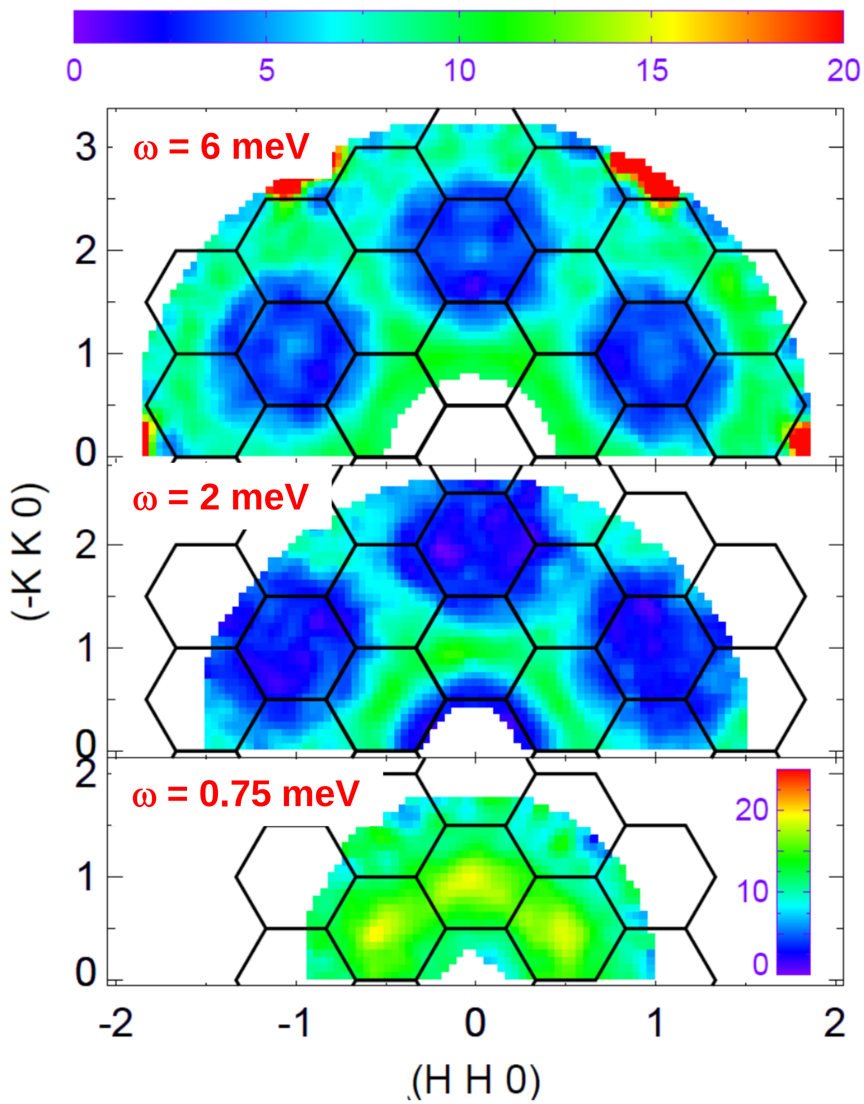
ω=0
no Bragg
peaks

A possible ω≠0 slice (theory)



Tchernyshyov et al (2010)

Spin correlations of the S=1/2 kagomé antiferromagnet



T Han, YL, et al,
Nature 492, 406 (2012)

T = 1.6 K

Re:
magnetic coupling is ~17 meV

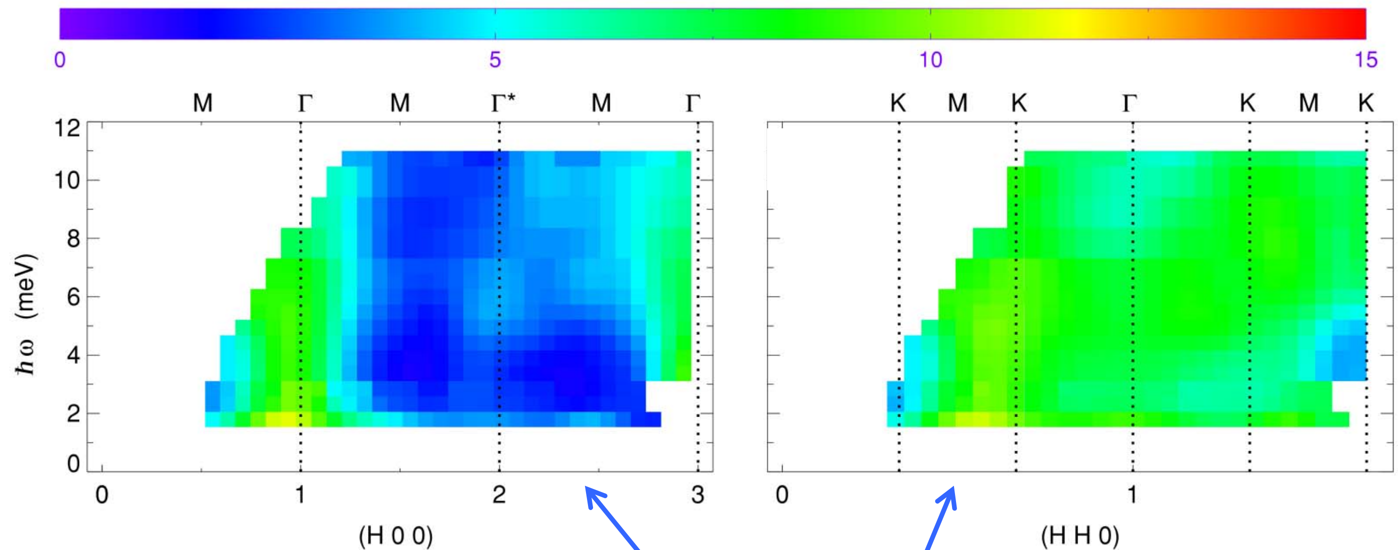
The observed scattering is:

- intrinsic to the kagomé spins
  (not just due to impurities)
- diffuse
  → no sharp dispersion surfaces !

Plots of $S(\vec{Q},\omega)$ (background measured with empty sample holder and subtracted)

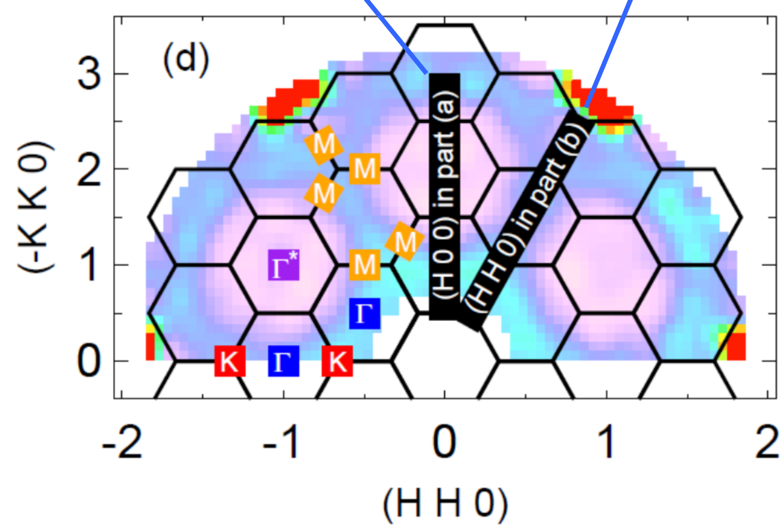
A <u>continuum</u> of spin excitations in a <u>two-dim</u> magnet

Direct evidence for spinons (fractionalized excitations)



S=1/2

$ZnCu_3(OD)_6Cl_2$



Integrating up to 11 meV, we see 20% of the total moment

Brief conclusions

1) Inelastic neutron scattering: ideal probe of phonons
and magnetic excitations of all kinds

2) Different techniques: (variations of triple-axis and time-of-flight)
think critically about your requirements
(resolution, sample size, etc…)

3) Enjoy your experiments. Good luck!