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SUMMER SCHOOL
on
LOW-DIMENSIONAL QUANTUM SYSTEMS:
Theory and Experiment
(16 - 27 JULY 2001)

PLUS

PRE-TUTORIAL SESSIONS
(11 - 13 JULY 2001)

FULL FERROMAGNETIC SATURATION OF A 2D QUANTUM ANTIFERROMAGNET

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Full Ferromagnetic Saturation of a 2D Quantum Antiferromagnet

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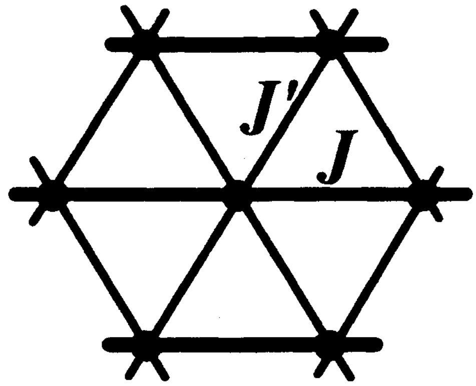


$S = 1/2$

<u>Outline of talk</u>

1. Introduction
2. Fully-polarized phase of a quantum magnet
3. Experiments on frustrated magnet Cs_2CuCl_4
4. Transition out of full alignment (Bose condensation of magnons)
5. Conclusions

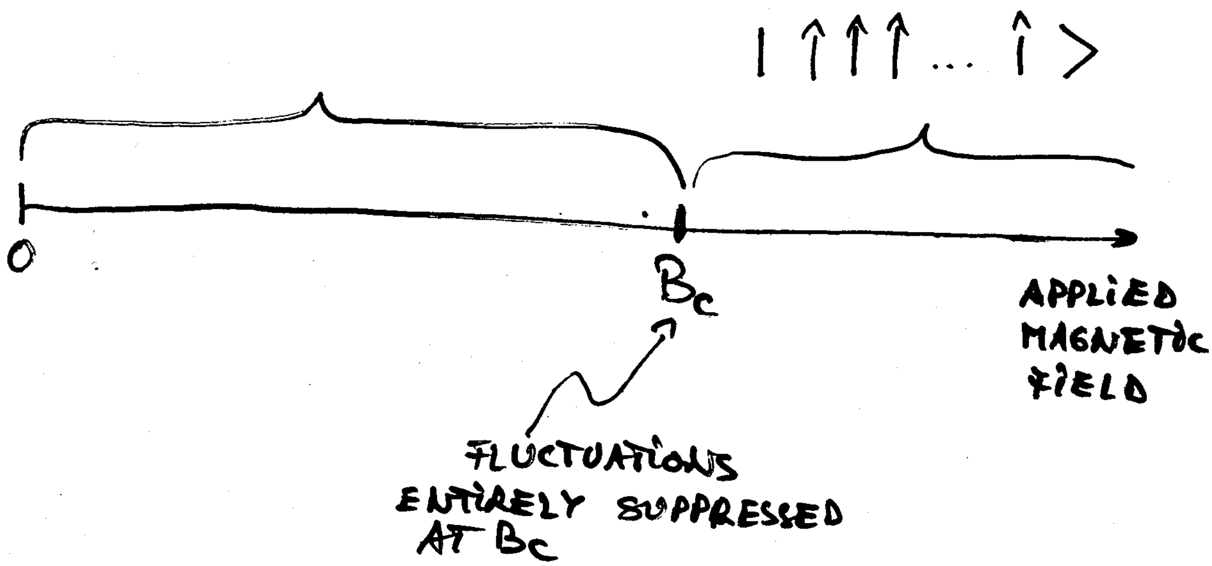
INTRODUCTION

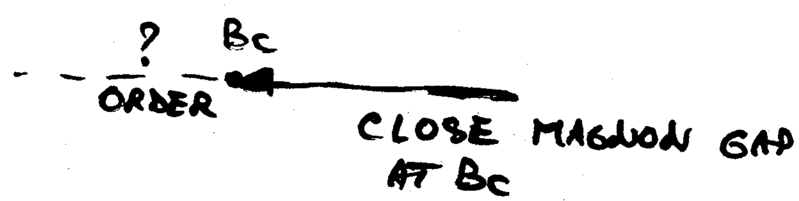
- USE APPLIED MAGNETIC FIELDS TO MANIPULATE GROUND-STATE FLUCTUATIONS IN A QUANTUM MAGNET

PHASES SHOWING STRONG FLUCTUATIONS

E.g. QUANTUM RENORMALIZATIONS
DECONFINED SPINONS
....

FULLY-POLARIZED PHASE
(NO FLUCTUATIONS)
SPIN-1 MAGNONS



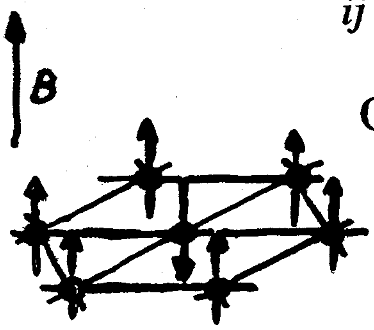


Excitations in the fully-polarized phase

- neutrons flip over one spin $\quad S^{-}|\uparrow\uparrow\uparrow\uparrow\uparrow\cdots\rangle = |\uparrow\uparrow\downarrow\uparrow\uparrow\cdots\rangle$

$$H = \sum_{ij} J_{ij}\, \mathbf{S}_i \cdot \mathbf{S}_j - h \sum_i S_i^z$$

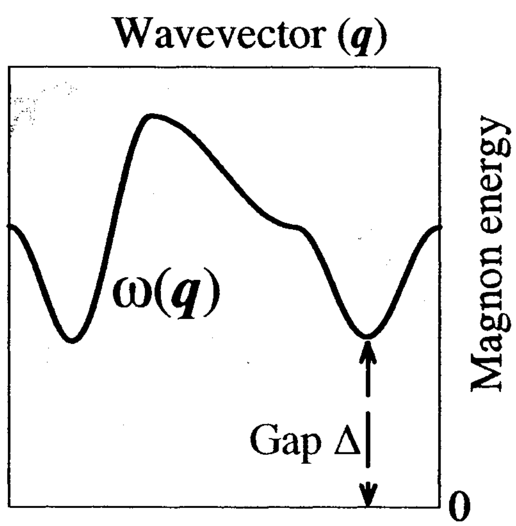
$$= \sum_{ij} \frac{J_{ij}}{2} (S_i^- S_j^+ + S_i^+ S_j^-) + \sum_{ij} J_{ij}\, S_i^z S_j^z - h \sum_i S_i^z$$



One spin flip $\Delta S^z = -1$ manifold of states

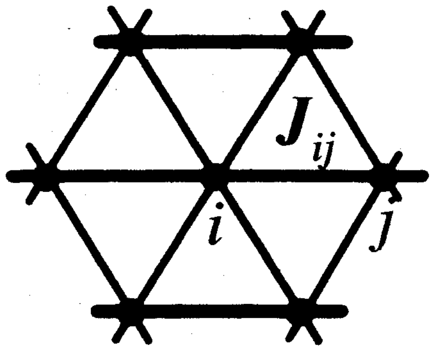
$$\left\{ |\uparrow\uparrow\downarrow\uparrow\uparrow\cdots\rangle \right.$$

fully-aligned eigenstate $|\uparrow\uparrow\uparrow\uparrow\uparrow\cdots\rangle \xrightarrow{S^-}$



magnon wavefunction $\quad |\varphi_q\rangle = \frac{1}{\sqrt{N}} \sum_i e^{i\mathbf{q}\mathbf{r}_i} |\downarrow_i\rangle$

energy $\quad \omega(\mathbf{q}) = J(\mathbf{q}) - J(0) + h \quad$ exact result



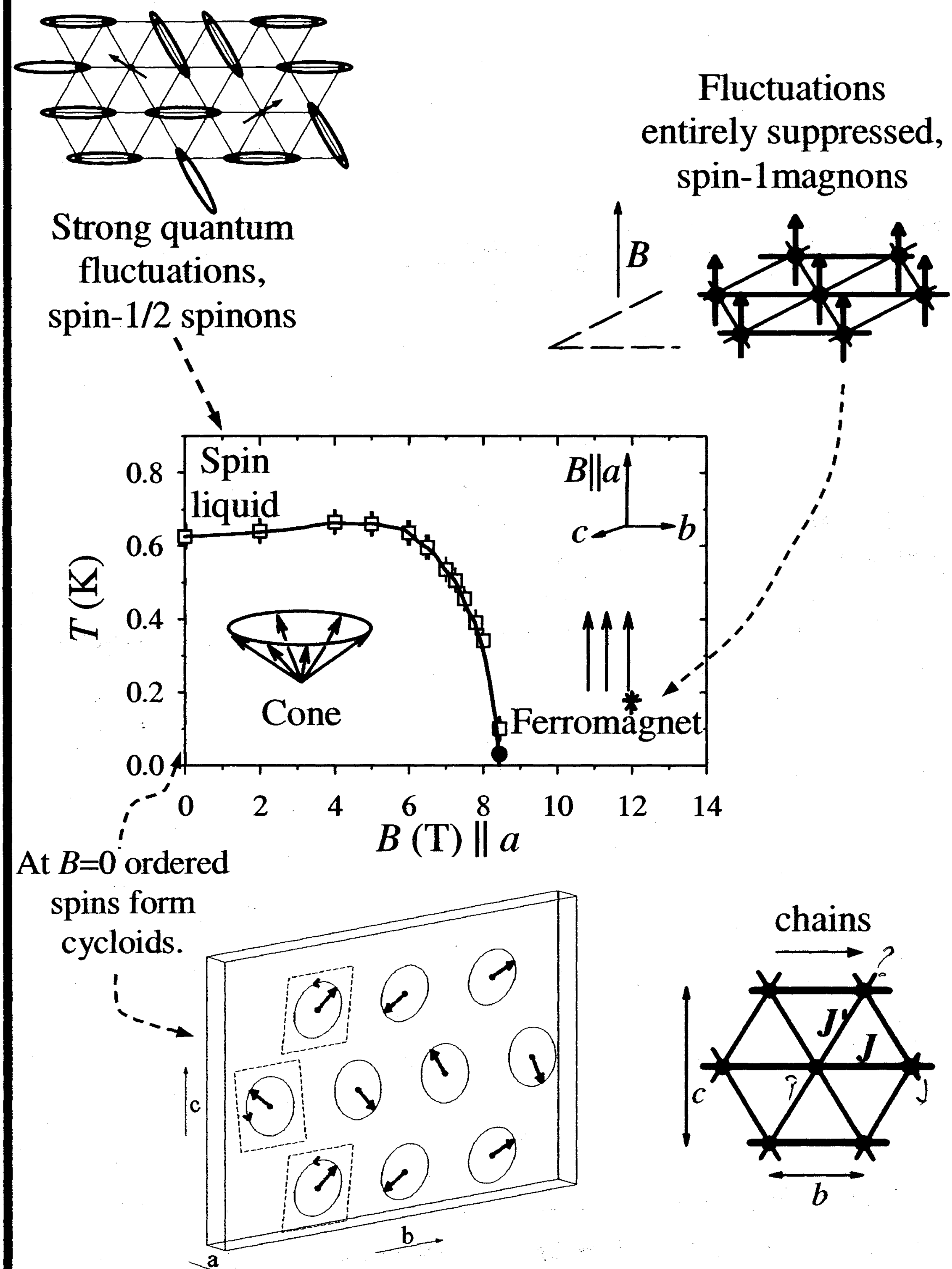
Fourier transform of magnetic couplings

$$J(\mathbf{q}) = \frac{1}{2} \sum_{ij} J_{ij}\, e^{i\mathbf{q}\mathbf{r}_{ij}}$$

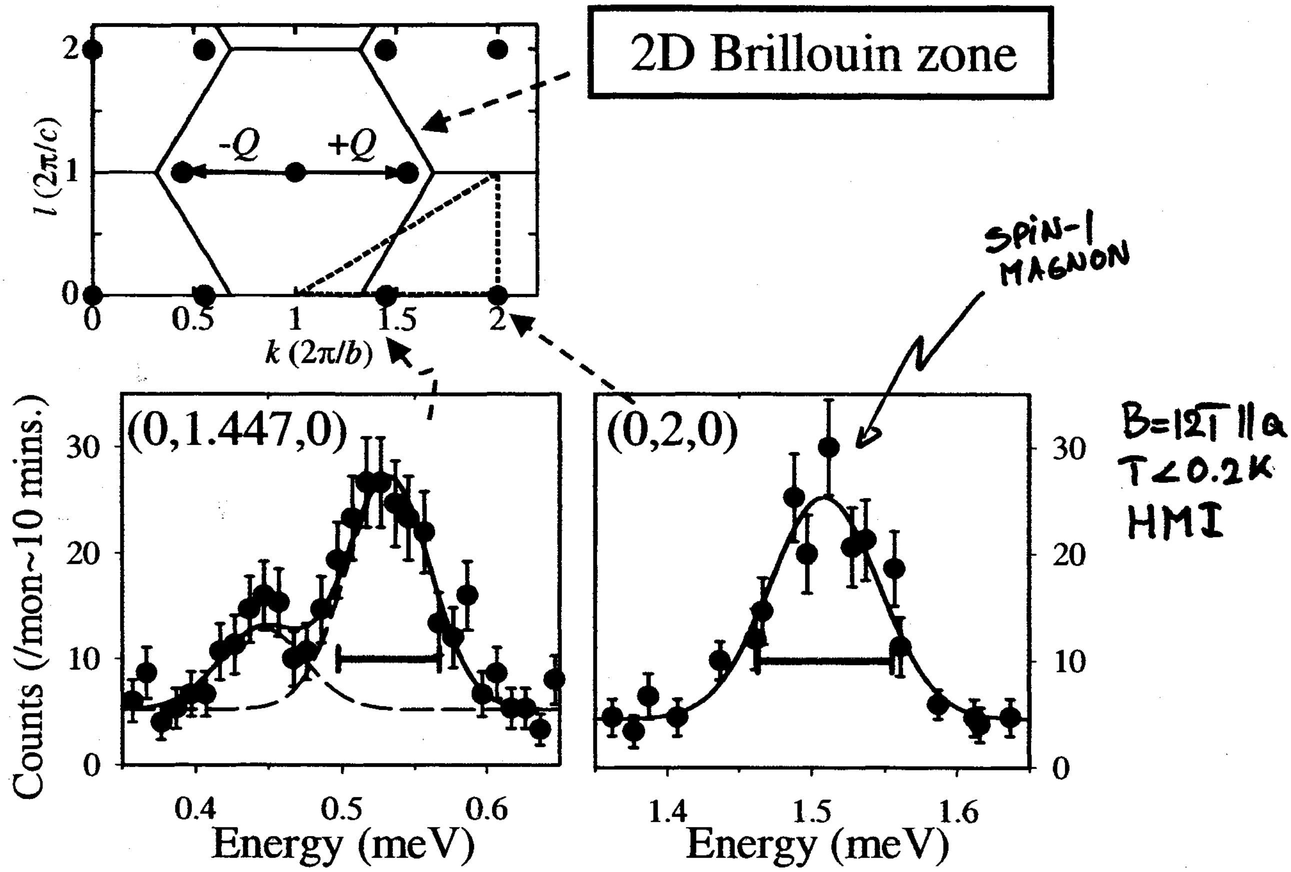
Zeeman energy

Excitations wavefunctions are known exactly, dispersion images exchange Hamiltonian

2D Frustrated quantum magnet Cs_2CuCl_4

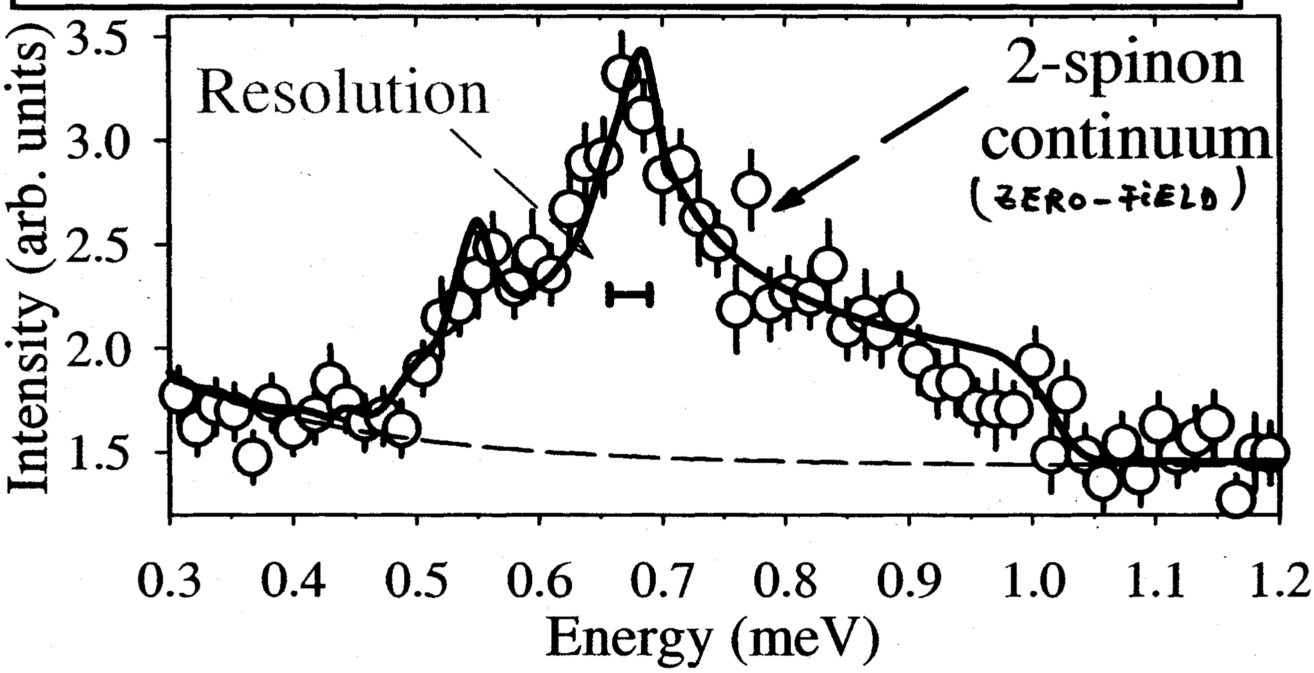


Excitations lineshapes in the fully saturated phase



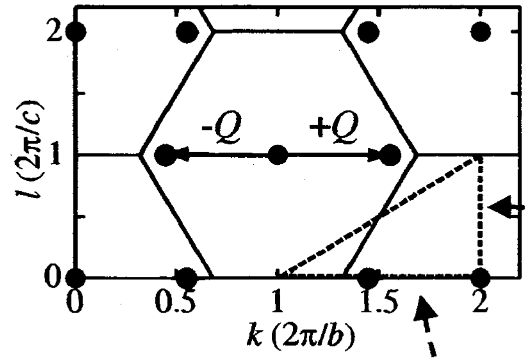
Lineshapes show well-defined, resolution-limited peaks as expected for spin-1 magnons

In contrast, in the spin-liquid phase ($B=0$) the lineshapes show a continuum arising from pairs of spin-1/2 spinons

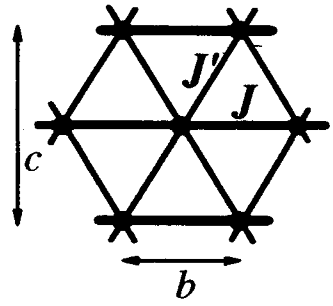


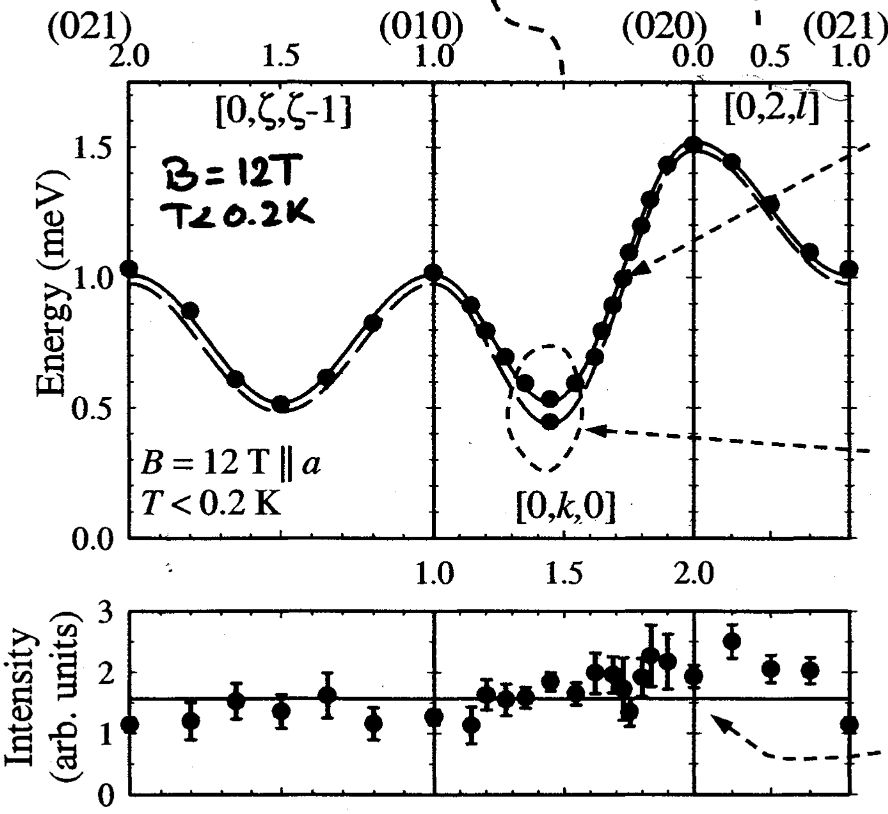
Dispersion relation and exchange constants

2D Brillouin zone



Triangular lattice

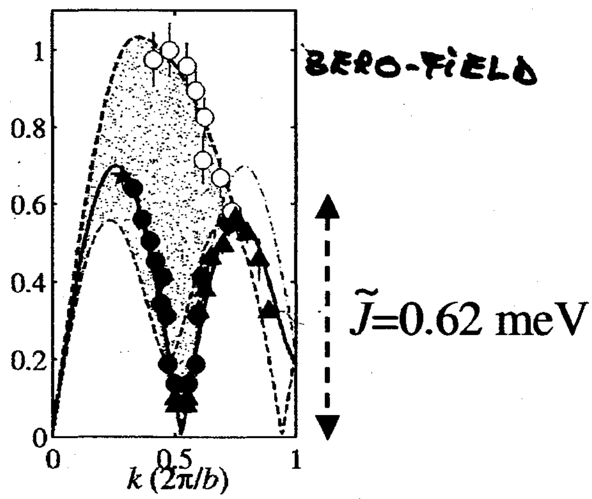




Overall shape is Fourier transform of exchanges $J(\boldsymbol{q})$:
J=0.375 meV
J'/J=0.33
⇓
2D Hamiltonian

Small splitting is due to anisotropy

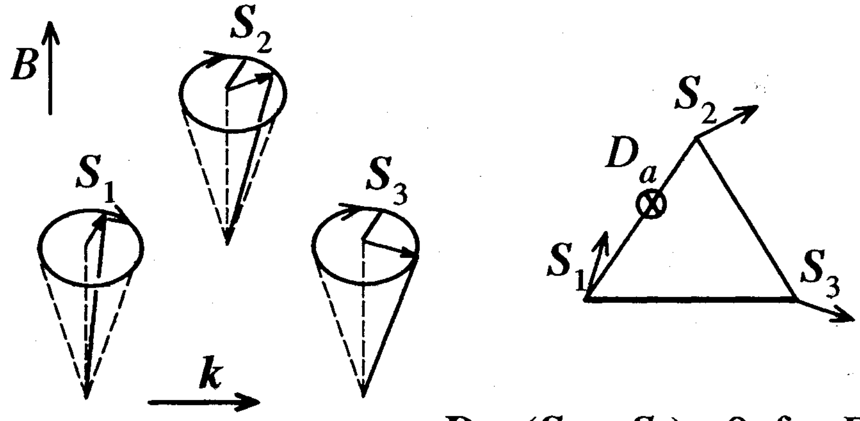
Constant intensity is signature of full ferromagnetic alignment



In contrast, in the B=0 spin liquid phase quantum fluctuations renormalize dispersion $R=\tilde{J}/J$=1.65 (π/2 in 1D)

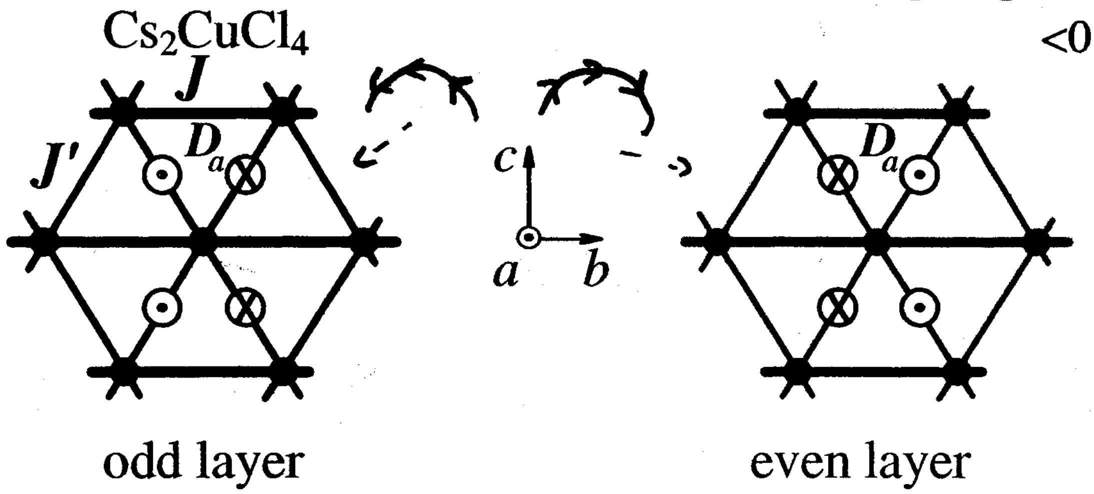
Splitting and Dzyaloshinskii-Moriya couplings

A $\Delta S^z = -1$
magnon is a
spin-wave
precession with
a well-defined
sense at given $\boldsymbol{k}$

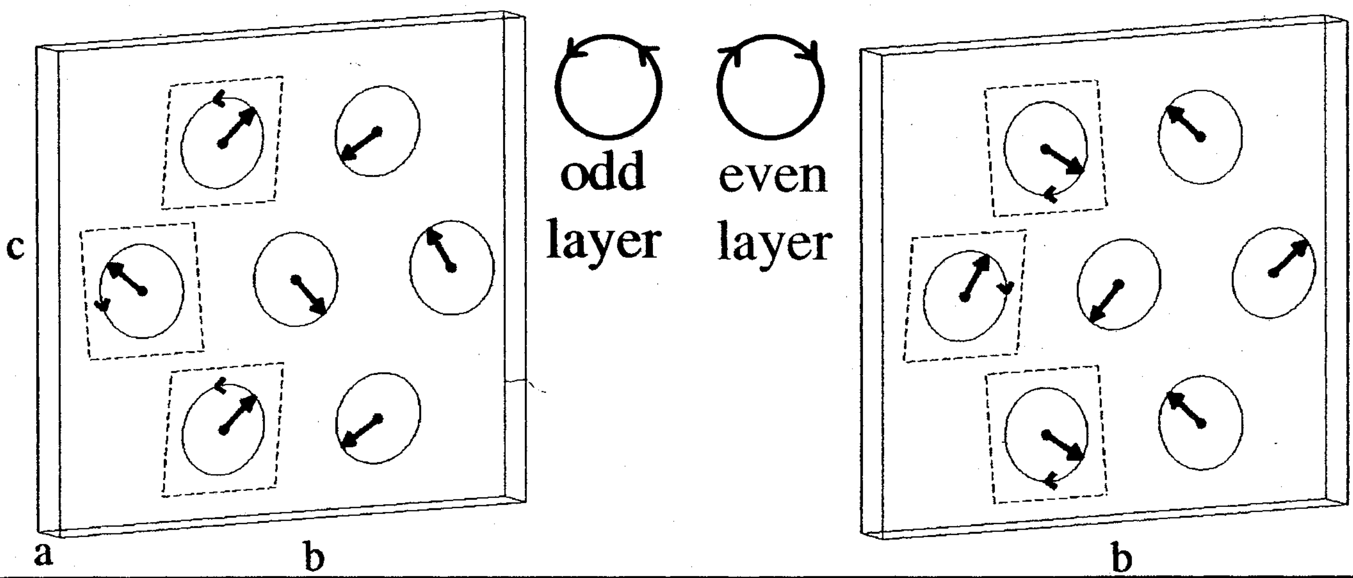


$\boldsymbol{D}a\ (\boldsymbol{S}_1 \times \boldsymbol{S}_2) > 0$ for $D_a > 0$

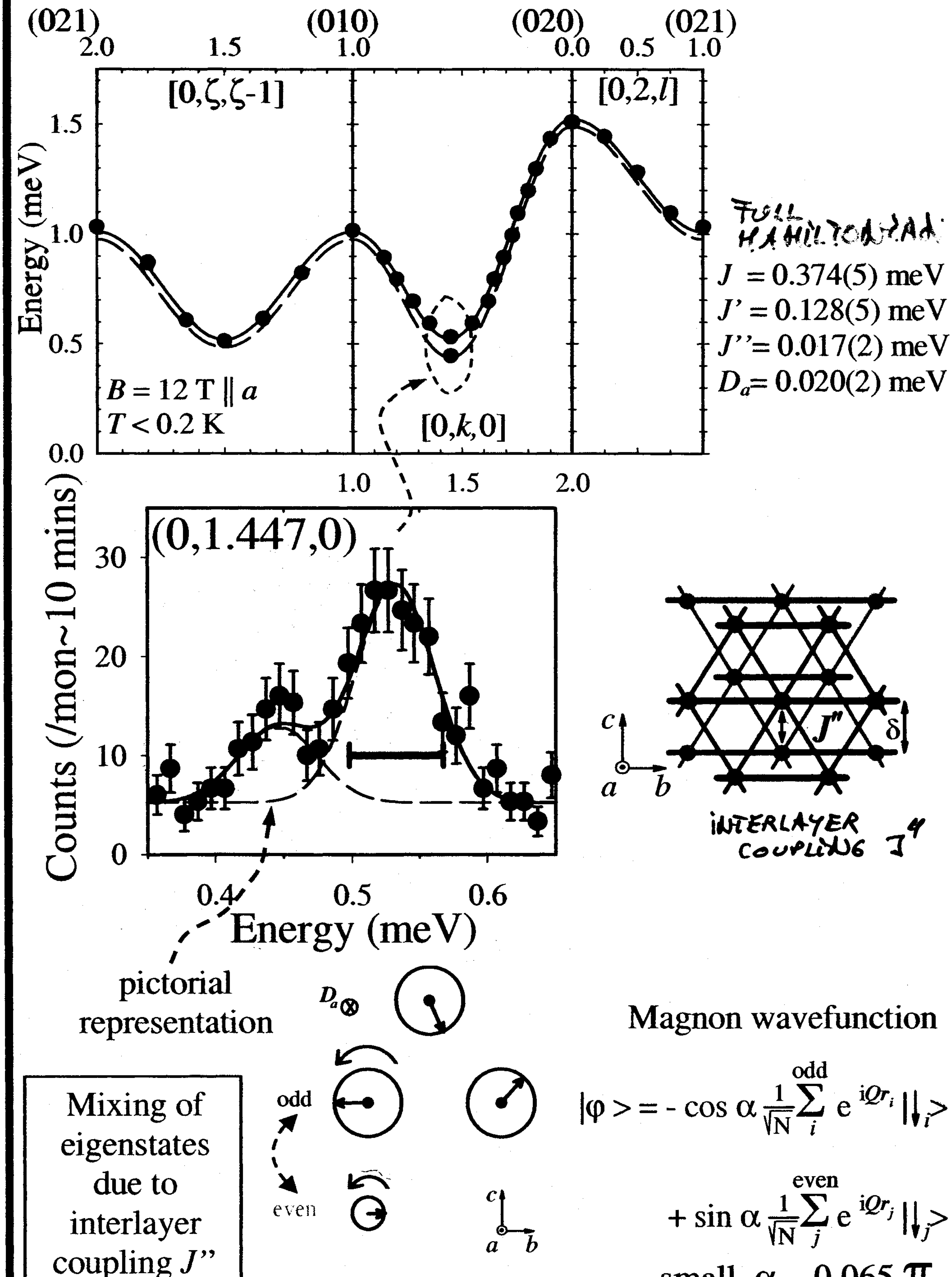
< 0 for $D_a < 0$



Local DM couplings favour same sense of rotation in one
layer and opposite sense in adjacent layers
=> splitting between odd/even layers ~ $D(\boldsymbol{q})$
=> counter-rotating layers in the B=0 cycloids



Dispersion relation and magnon wavefunctions



Magnon wavefunction

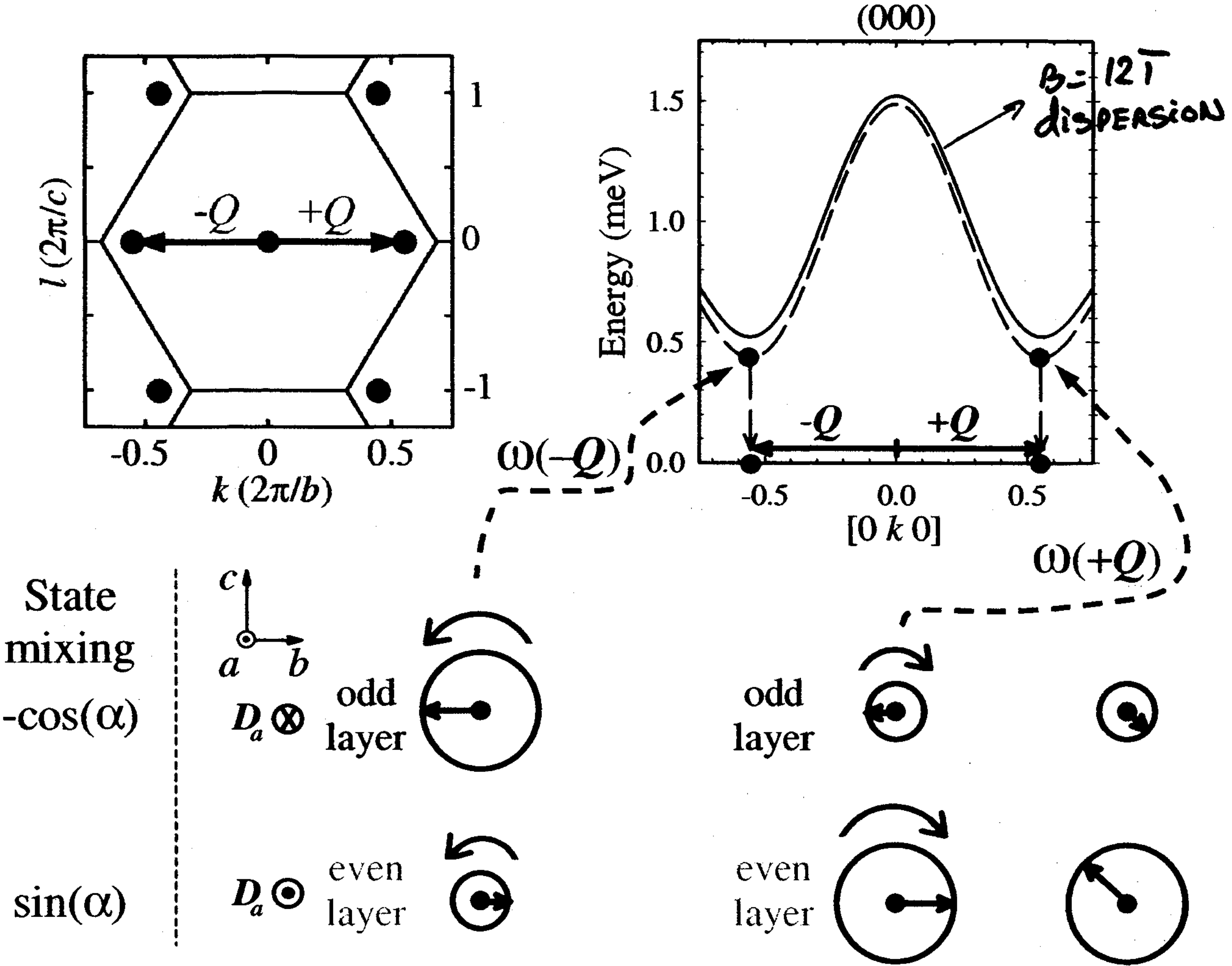
$$|\varphi\rangle = -\cos\alpha \frac{1}{\sqrt{N}} \sum_{i}^{\text{odd}} e^{iQr_i} |\downarrow_i\rangle$$

$$+ \sin\alpha \frac{1}{\sqrt{N}} \sum_{j}^{\text{even}} e^{iQr_j} |\downarrow_j\rangle$$

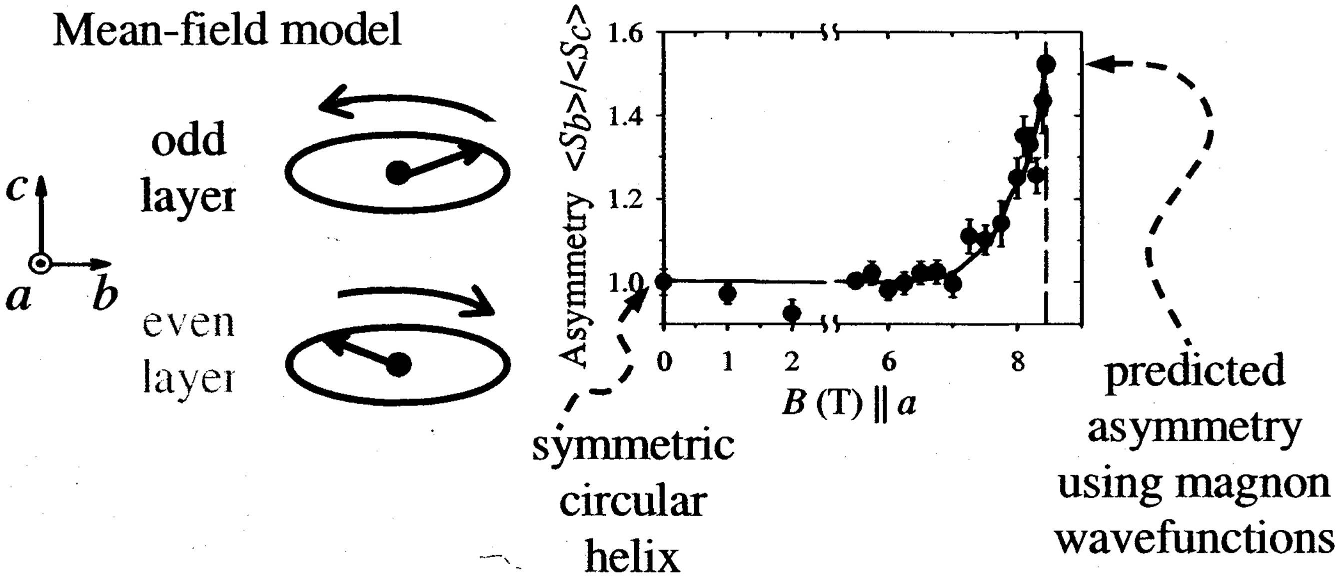
small $\alpha \sim 0.065\,\pi$

Mixing of eigenstates due to interlayer coupling J''

Long-range order as a condensation of magnons

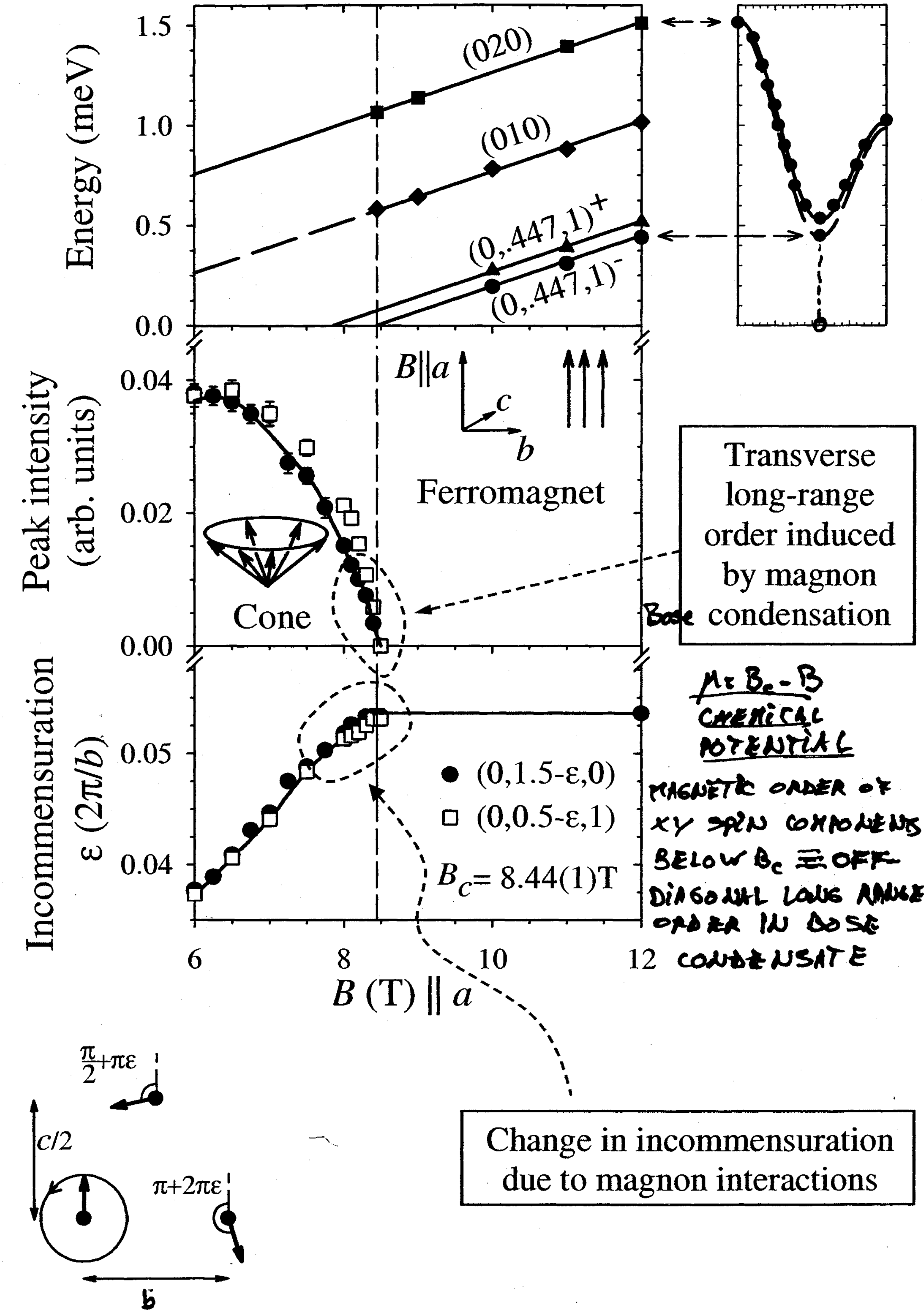


Simultaneous condensation at $-Q$ and $+Q$ => elliptical order



The wavefunction of the magnetic order can be constructed from the wavefunctions of the condensed magnons

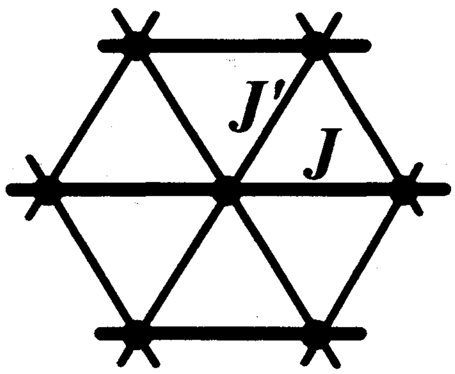
Closing the magnon gap and onset of long-range order



Conclusions

1. Full ferromagnetic saturation prepares a magnet in a phase where the ground state and all excited states have exactly known wavefunctions. Experimental measurement of the excitations in this phase gives the bare Hamiltonian with absolute (un-renormalized) values for all couplings.

2. For strongly fluctuating magnets this is a uniquely powerful method to experimentally determine ground-state energies and quantum renormalizations.



2D frustrated quantum magnet Cs_2CuCl_4 (J'/J=0.33)

3. Closing the magnon gap at the saturation field allows studies of the conditions in which order arises from condensation of particles in the ground state ($B_c - B = \mu$ chemical potential for Bose condensation)