Recap

- Energy scales
  - Exchange interaction
  - Crystal field
- Scattering
  - Weak scattering potential (x-ray/neutron)
  - Born approximation

$$\frac{d^2\sigma}{d\Omega} \propto |U(\vec{q})|^2 \, S(\vec{q}) \quad \text{, single atom case}$$

$\uparrow$ F.T. of correlation fn

  - Crystal with a basis

$$\frac{d^2\sigma}{d\Omega} \propto \Big|\underbrace{\sum_{\vec{r}_j} f_j(\vec{q}) e^{i\vec{q}\cdot\vec{r}_j}}_{\text{unitcell structure factor}}\Big|^2 \delta(\vec{q}-\vec{G})$$

Order

- Broken symmetry
- Observed with scattering (Bragg peaks)
- We will look at some examples

Liquid crystals

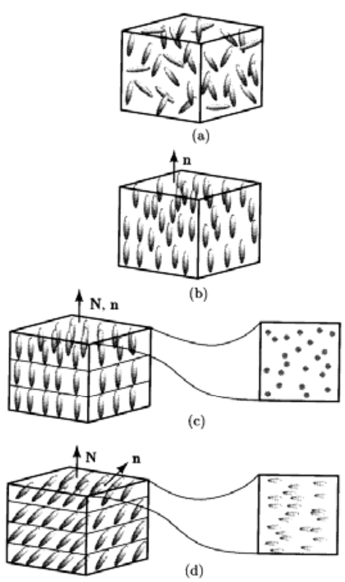
Karen Neill , Wellcome images

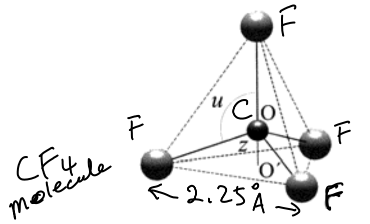
Isotropic | Broken symmetry

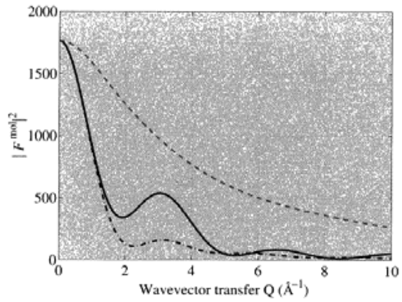
Nematic | Rotational

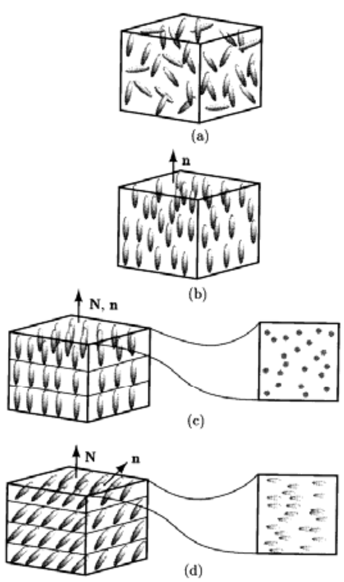
Smectic A | Rotational+Translational

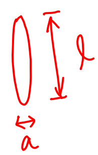
Smectic C | Rotational+Translational

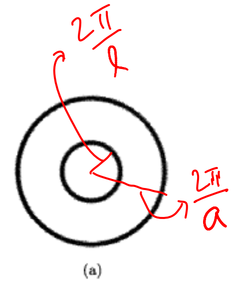


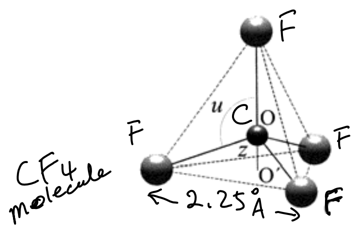

F
u
C
O
z
O'
F
F
F
CF_4 molecule
2.25 Å

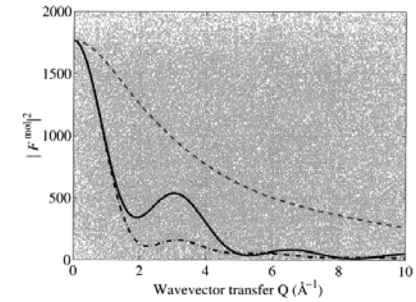

2000
1500
1000
500
0
$|F^{mol}|^2$
0
2
4
6
8
10
Wavevector transfer Q (Å^{-1})

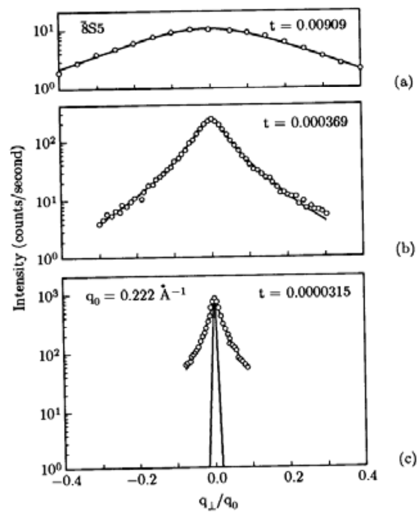

n
N, n
N
(a)
(b)
(c)
(d)


l
a


$\frac{2\pi}{l}$
$\frac{2\pi}{a}$
(a)

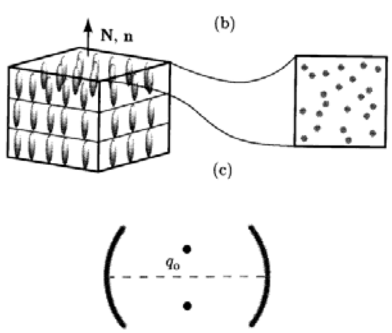


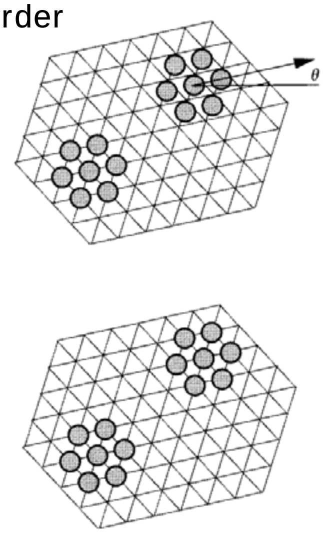


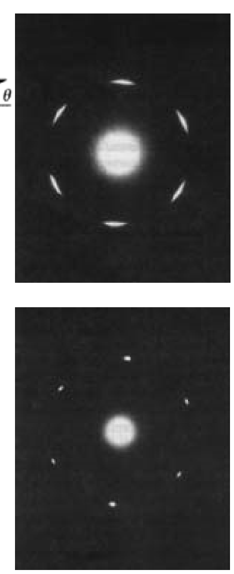


Hexatic phase

- Bond orientational order



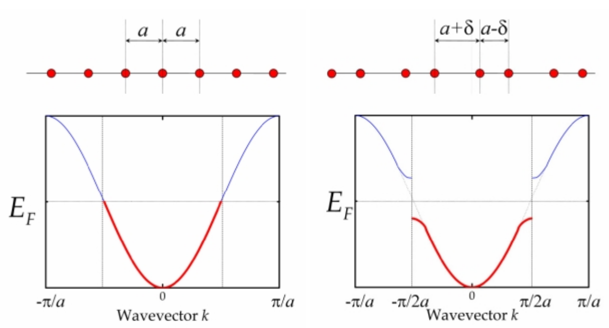




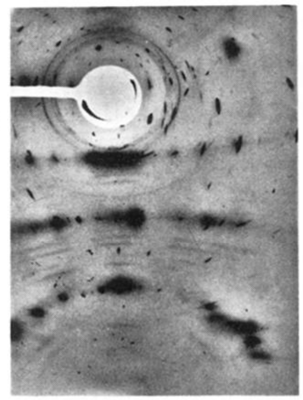
Charge Density Wave

- Example: Peierls distortion

TTF-TCNQ Pouget et al.

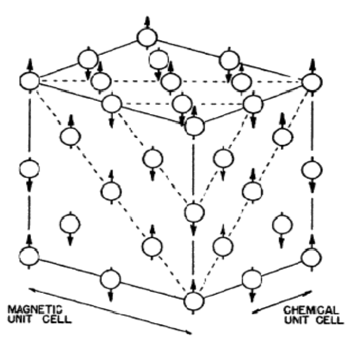


(a) (b)

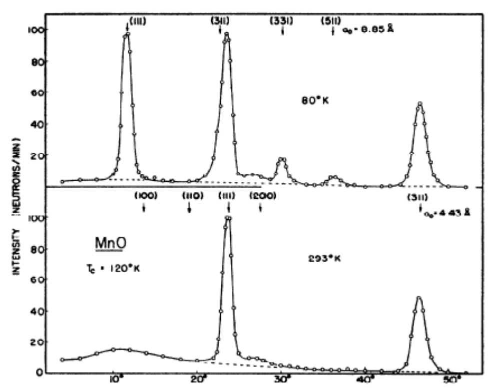


Quasi 1D order

Magnetic order



Mn ATOMS IN MnO



C. G. Shull, Phys. Rev. (1951)

Magnetic neutron scattering

- neutron magnetic moment: $\boldsymbol{\mu} = \gamma \mu_N \boldsymbol{\sigma}$
- Magnetic field due to a single electron:

$$\mathbf{H} = \nabla \times \left(\frac{\boldsymbol{\mu}_e \times \mathbf{R}}{R^3} \right) + \left(\frac{-e}{c} \right) \frac{\mathbf{v}_e \times \mathbf{R}}{R^3}$$

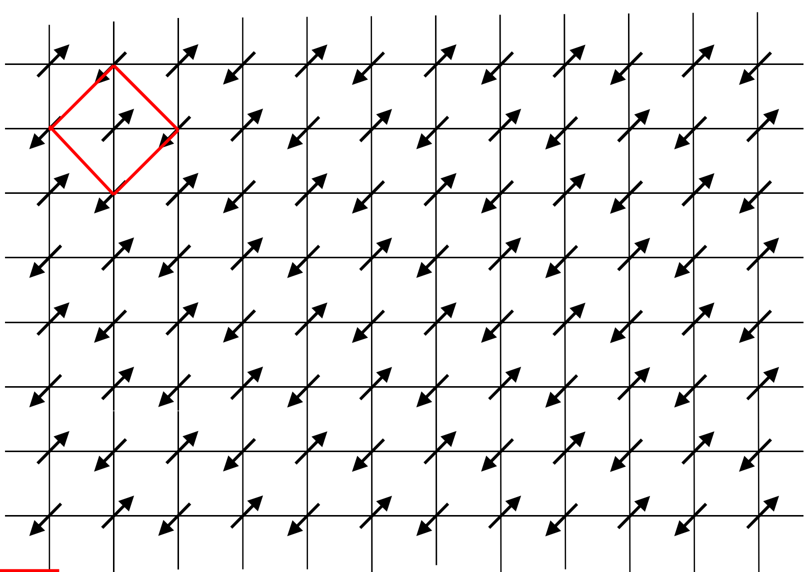
- Scattering cross section: Use Fermi's Golden rule

$$\frac{d^2\sigma}{d\Omega dE_f} = (\gamma r_0)^2 \frac{k_f}{k_i} N \left[\frac{g}{2} f(\mathbf{Q}) e^{-W} \right]^2 \sum_{\alpha\beta} (\delta_{\alpha\beta} - \hat{Q}_\alpha \hat{Q}_\beta) S^{\alpha\beta}(\mathbf{Q}, \omega)$$

$$f(\mathbf{Q}) = \int s(\mathbf{r}) e^{i\mathbf{Q}\cdot\mathbf{r}} d\mathbf{r}$$

$$S^{\alpha\beta}(\mathbf{Q}, \omega) = \frac{1}{2\pi} \sum_{\mathbf{r}} \int_{-\infty}^{\infty} dt\, e^{i(\mathbf{Q}\cdot\mathbf{r} - \omega t)} \left\langle S^\alpha(\mathbf{0}, 0) S^\beta(\mathbf{r}, t) \right\rangle$$

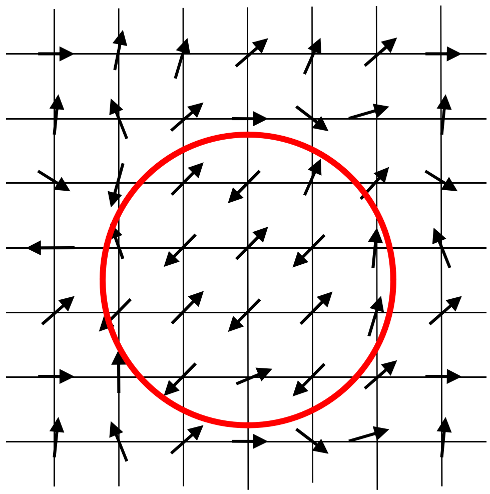
$$S^{\alpha\beta}(\mathbf{Q}) = \int_{-\infty}^{\infty} d\omega\, e^{i(\mathbf{Q}\cdot\mathbf{r} - \omega t)} S^{\alpha\beta}(\mathbf{Q}, \omega)$$

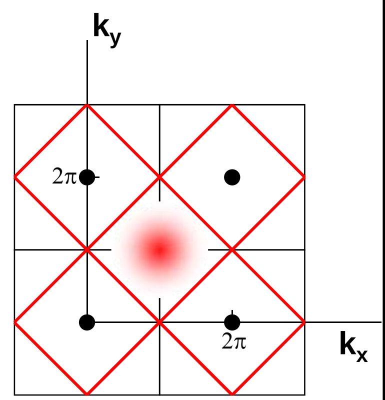


$\boxed{T = 0}$

Heisenberg model on 2D lattice $H = \sum J \mathbf{S}_i \cdot \mathbf{S}_j$

Short-range order ($T > T_N$)





Representative scans

Elastic (ω=0)
Bragg peak
(resolution limited)

Quasi-elastic (ω~0)
Finite Q width

Inelastic scan
Fixed Q
dispersion relation