# Today's program

## Exam information

Structure of Exam

Example of questions

## Magnetism: Continuation from last lecture

Magnetic structure
Magnetic excitations

## Phase transitions

Order parameters

Landau theory

## Superconductivity

Intro & applications
Specific heat

# Exam Structure

**10 min – Presentation:**

Topics: (1) Crystal structures, (2) Crystal Bindings, (3) Reciprocal lattice+ scattering theory,
(4) Crystal vibrations (Phonons), (5) Heat capacity (6) Band structure
(7) Semiconductors

**20 min – Discussion:**

(a) Questions to the lecture material
(b) Questions to the exercises

End Exam

5 min - evaluation

5 min – Results: Passed / failed, grade will be known at a later point.

**<u>MY AVAILABILITY BEFORE EXAM</u>**:
30$^{th}$-31th May
1st and 6$^{th}$ of June

johan.chang@physik.uzh.ch

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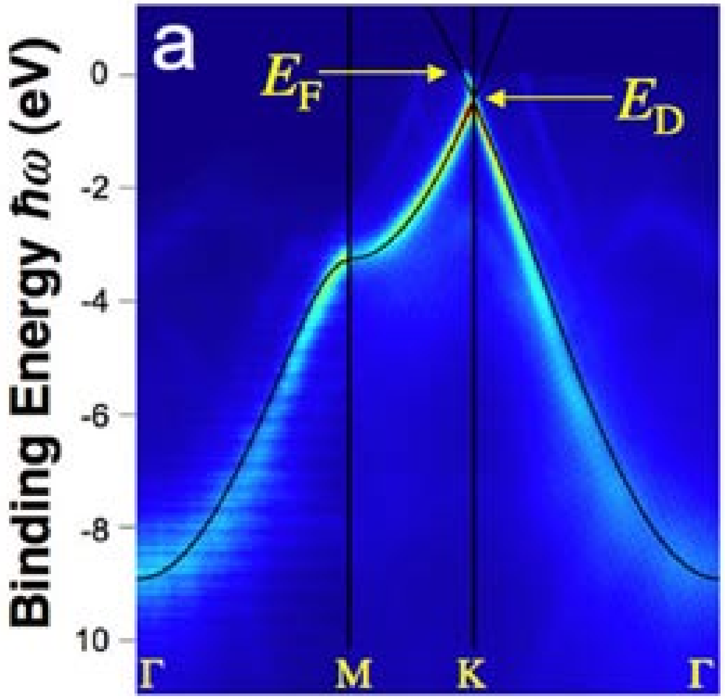
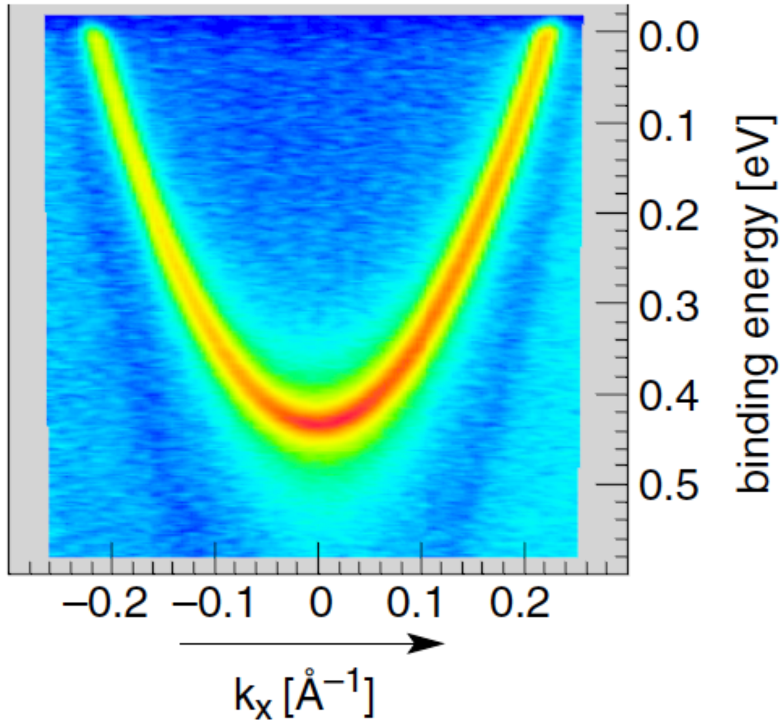
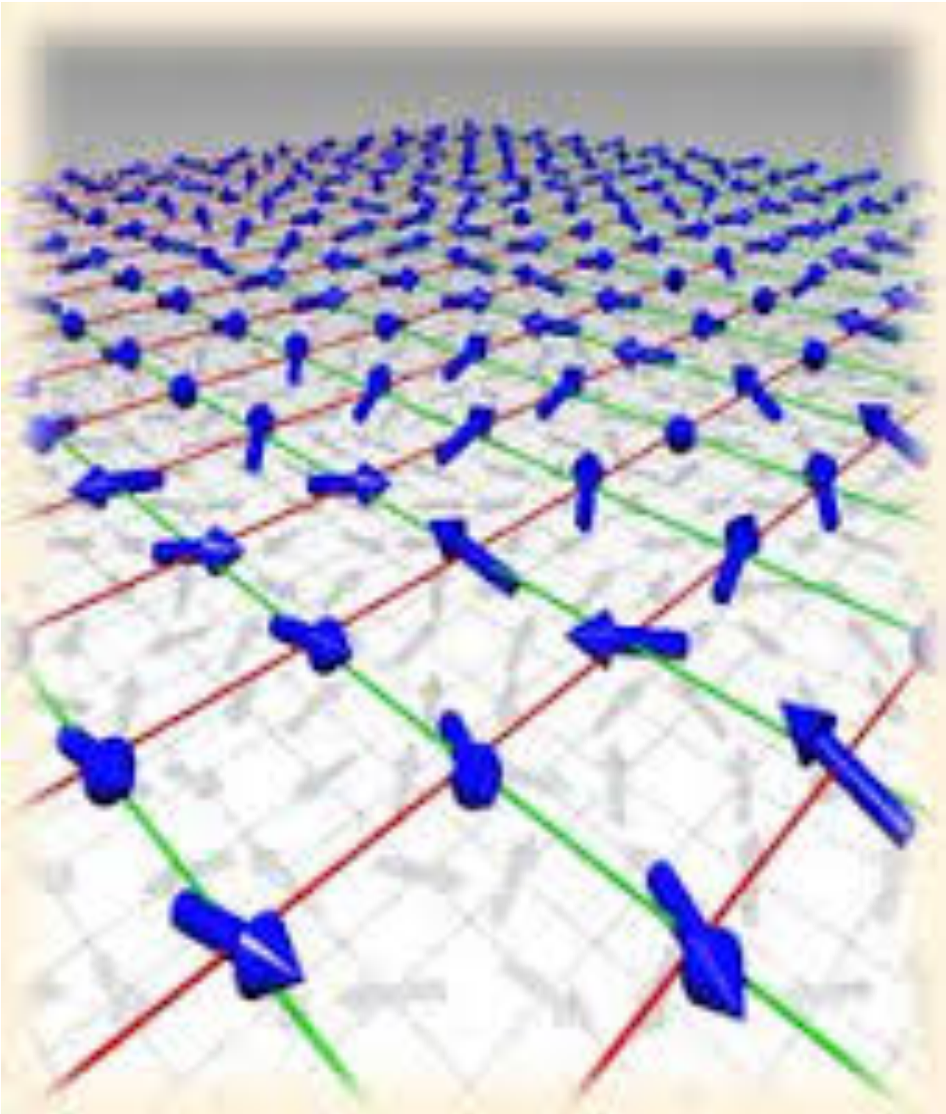
# Band structure




(1) Describe the figure. What is the band width?
(2) In the tight binding model what sets the band width?
(3) Can you draw the dispersion of a free electron?
(4) What is the implication of an electron sensing a periodic potential?

# 2-dimensional square lattice



**Heisenberg Model**

$$U = -J S_i \cdot S_j$$

**Nearest Neighbor Interaction**

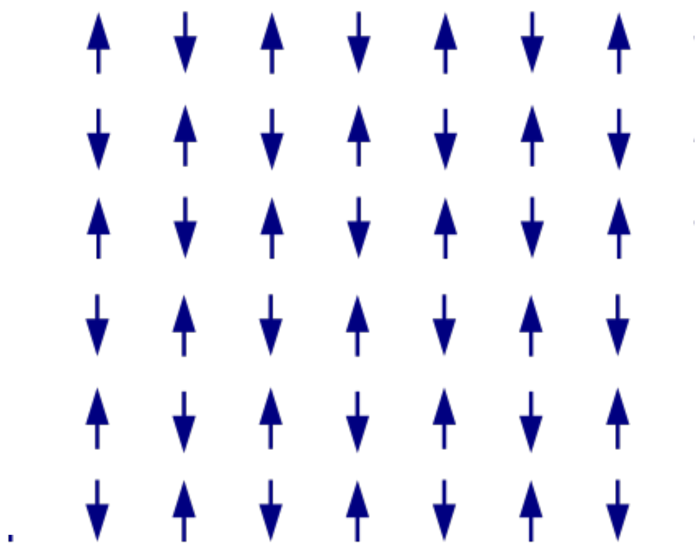
*J* = “Coupling between spins”

Nature likes to minimize the energy U!

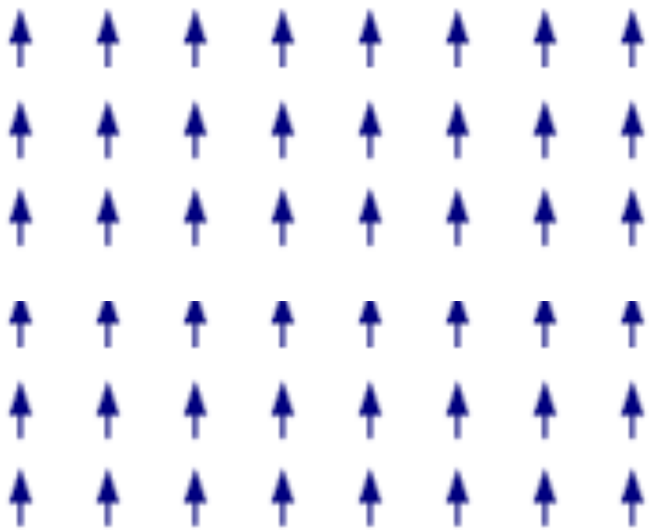
# Heisenberg Model

$$U = -JS_i \cdot S_j$$

**Anti-ferromagnetism**
**J < 0**



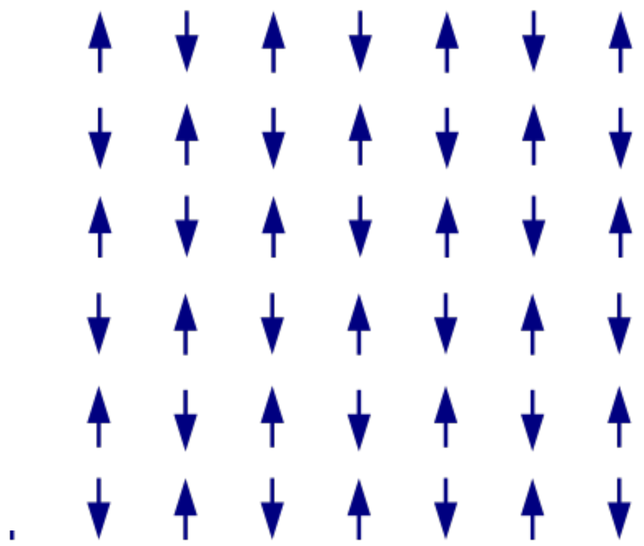
**Ferromagnetism**
**J > 0**



# Heisenberg Model

$$U = -J S_i \cdot S_j$$

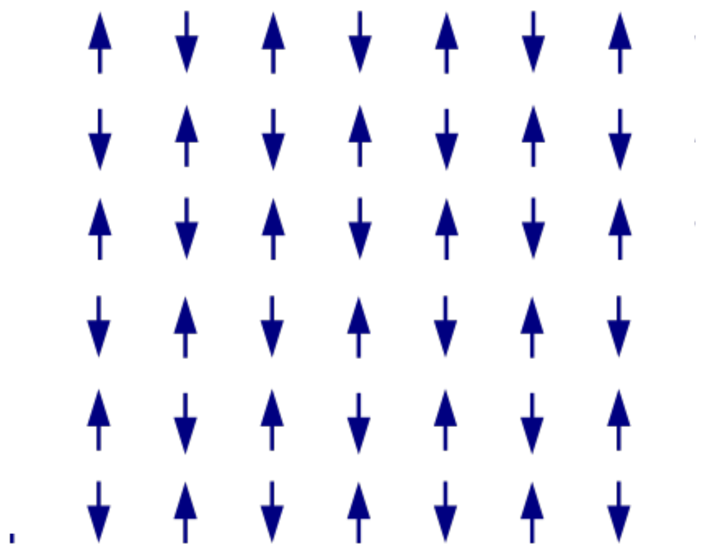
**Anti-ferromagnetism**
**J < 0**



1. What is the lattice parameter?
2. What happens to the unit cell?
3. What about the first Brillioun zone?

# Scattering theory: Magnetic Form Factor

**Anti-ferromagnetism**
**J < 0**



What is your expectation for the magnetic form factor?

# Scattering theory: Structure Factor

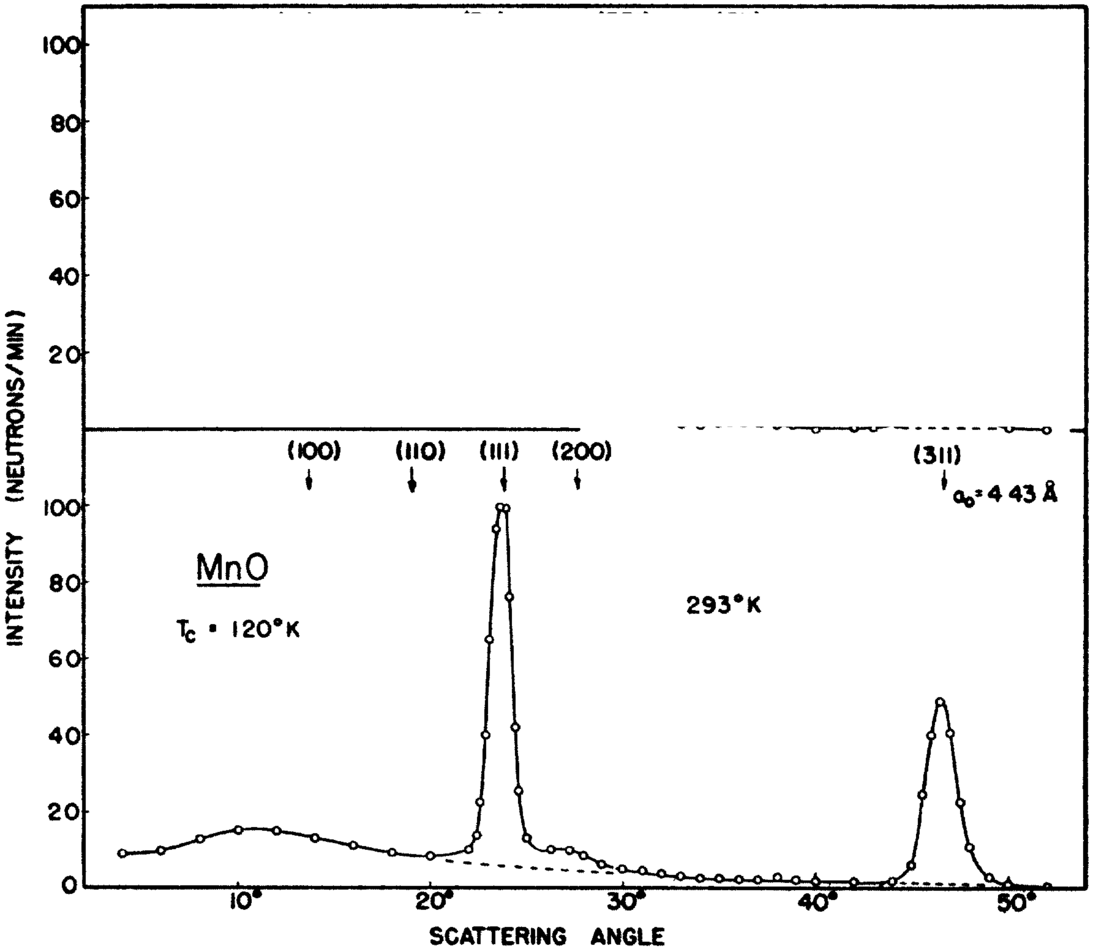



FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

**Example: MnO**

Atomic crystal lattice

NaCl – type structure

$S = 4\,(f_M - f_O)$ when hkl even
$S = 4\,(f_M + f_O)$ when hkl odd
$S = 0$ mixed parity

$f_M \sim -f_O$

# Scattering theory: Structure Factor

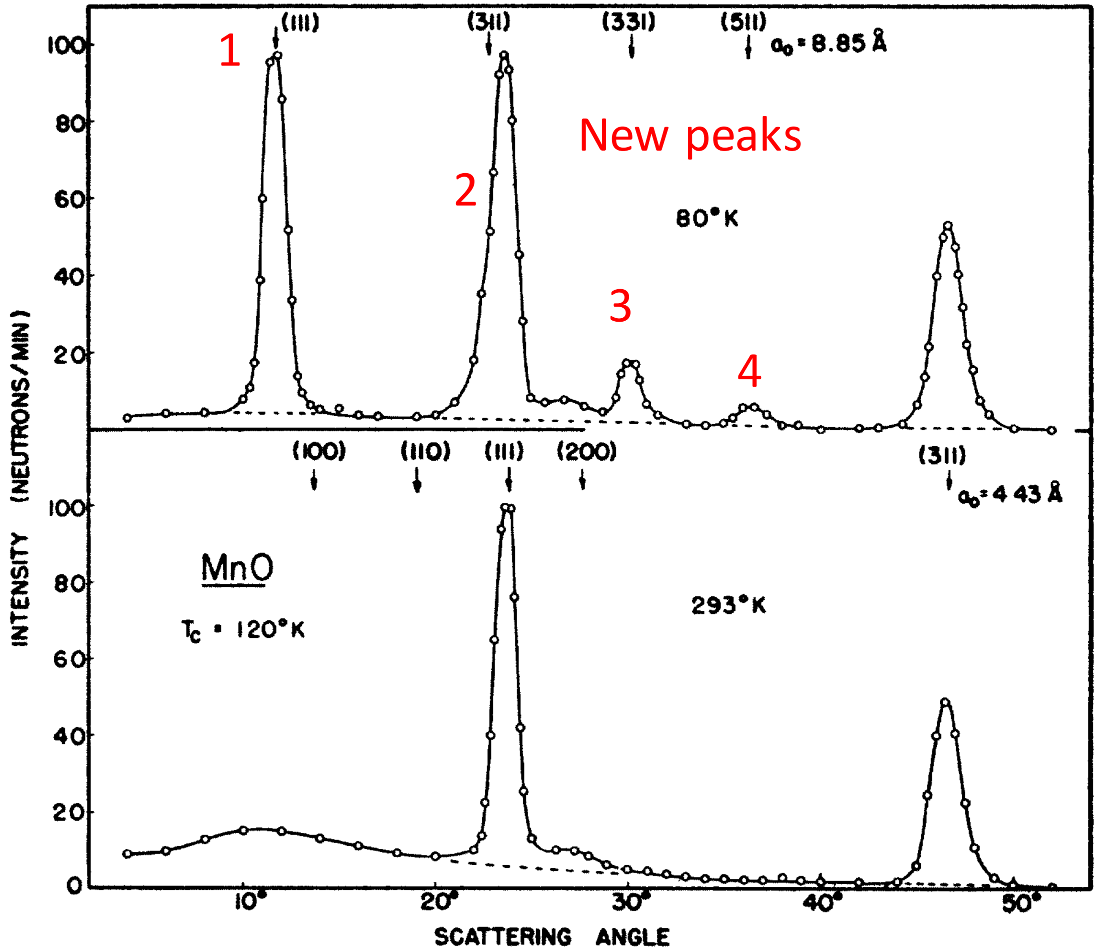



FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

Magnetic "Crystal" structure can be resolved.

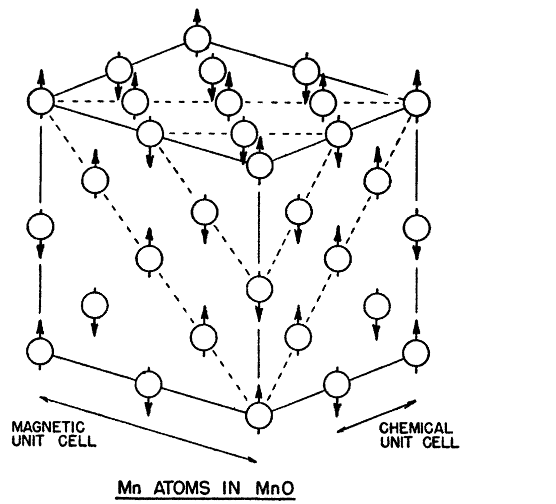
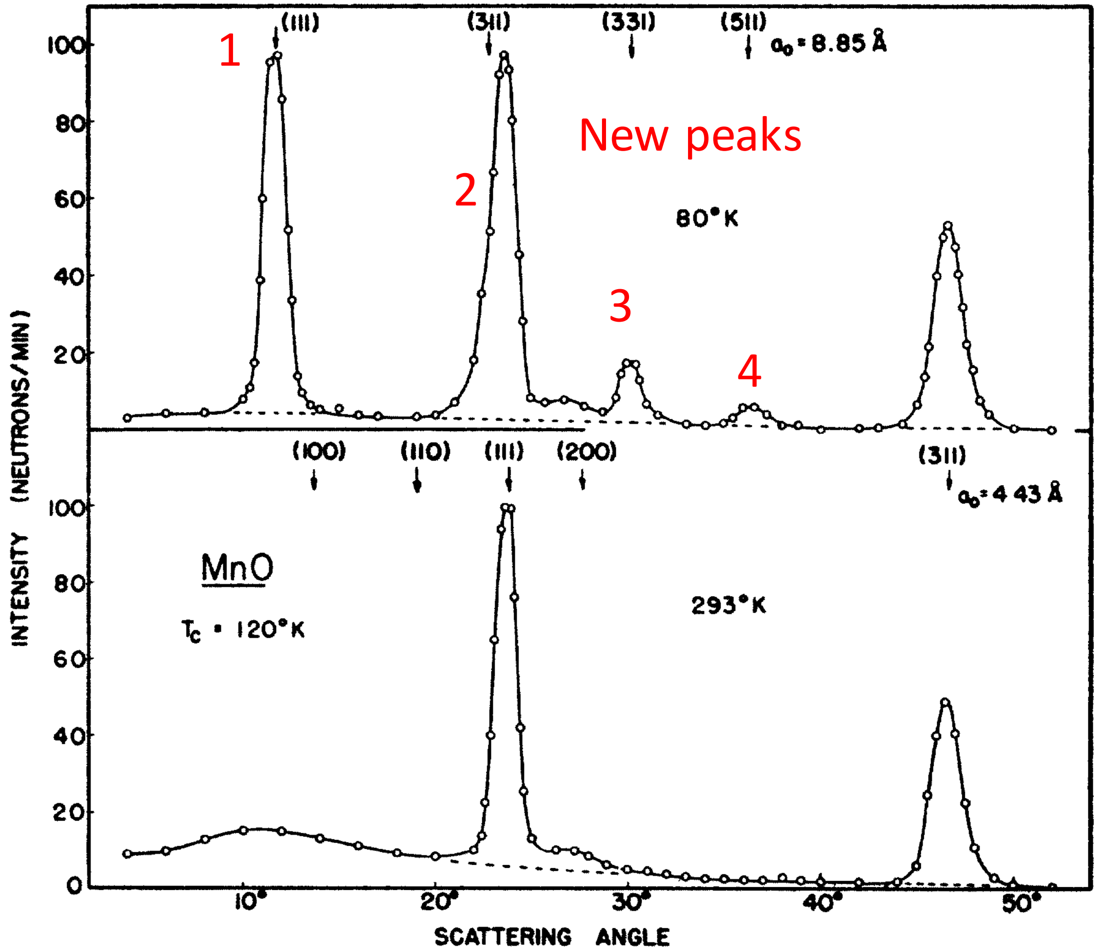



FIG. 5. Antiferromagnetic structure existing in MnO below its Curie temperature of 120°K. The magnetic unit cell has twice the linear dimensions of the chemical unit cell. Only Mn ions are shown in the diagram.

C. G. Shull *et al.*, Phys. Rev. 1951

# Scattering theory: Structure Factor

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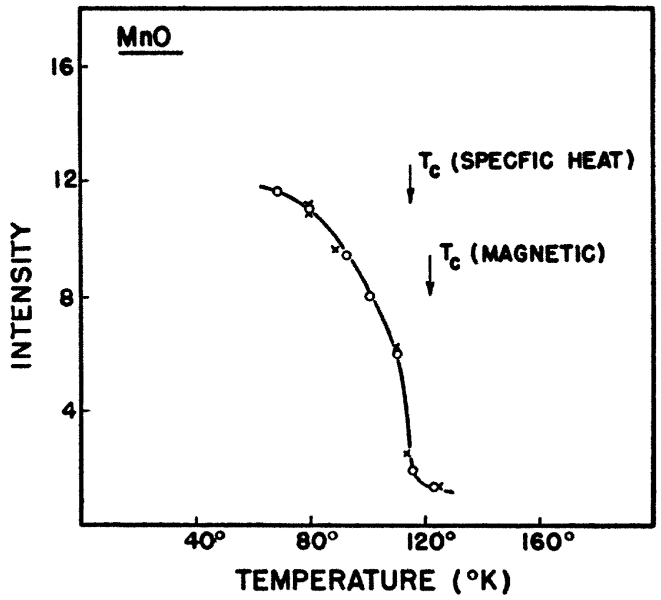
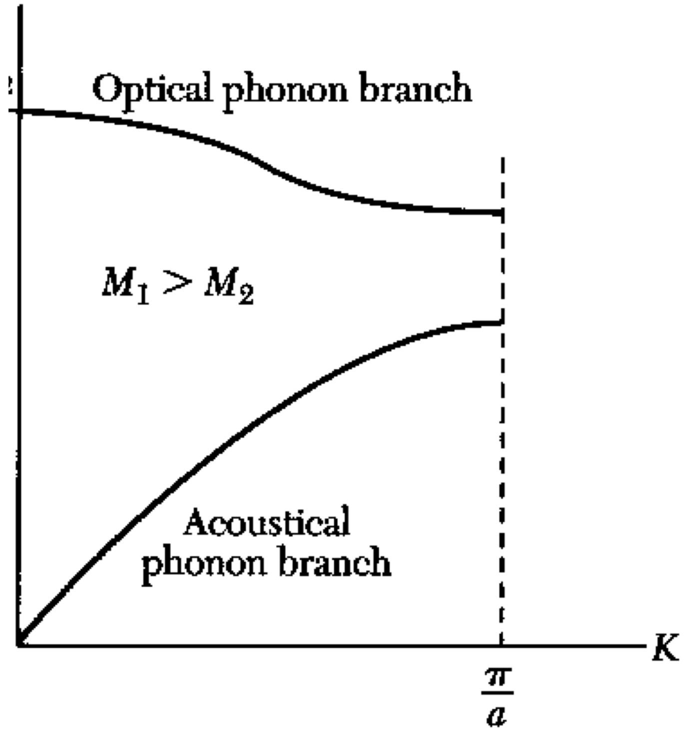
Magnetic phase transition



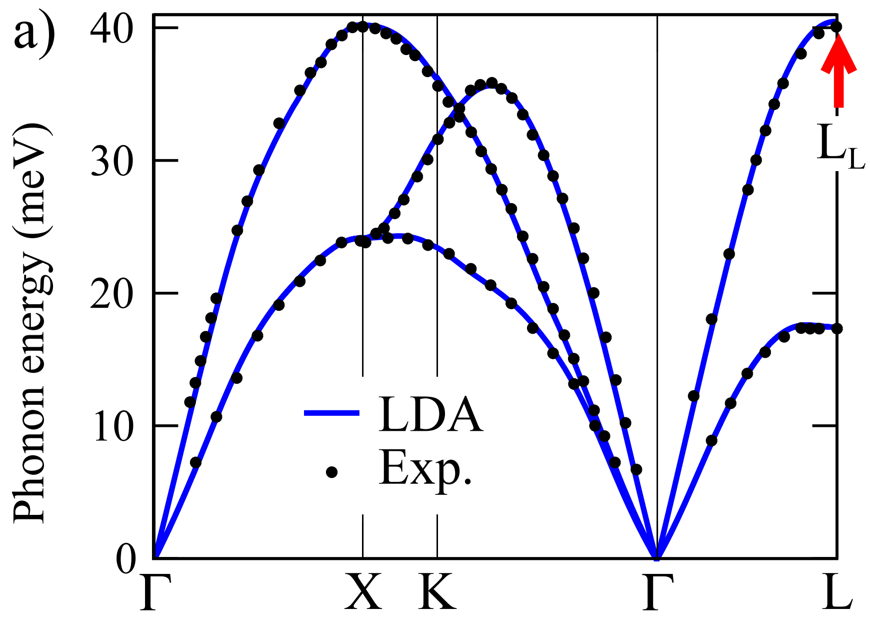

C. G. Shull *et al.*,
Phys. Rev. 1951

# Phonons – Lattice vibrations

Simple Model Calculation



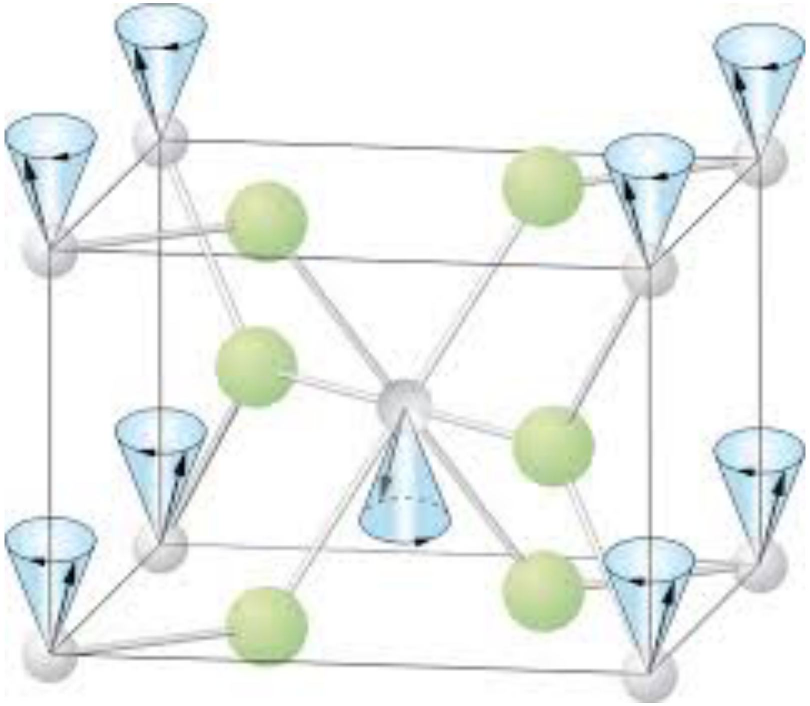

Phonons of Aluminium

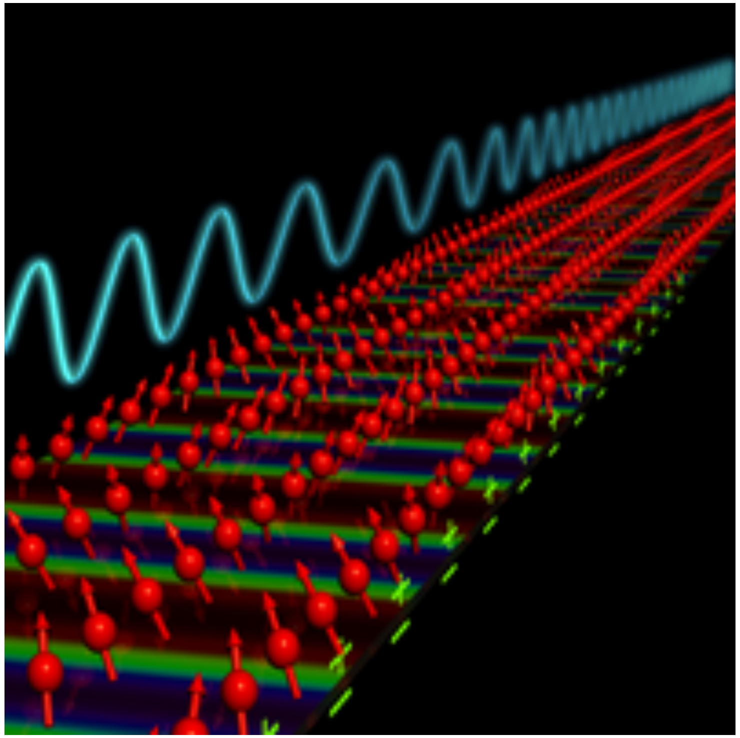



What determines the phonon dispersion at the zone boundary?

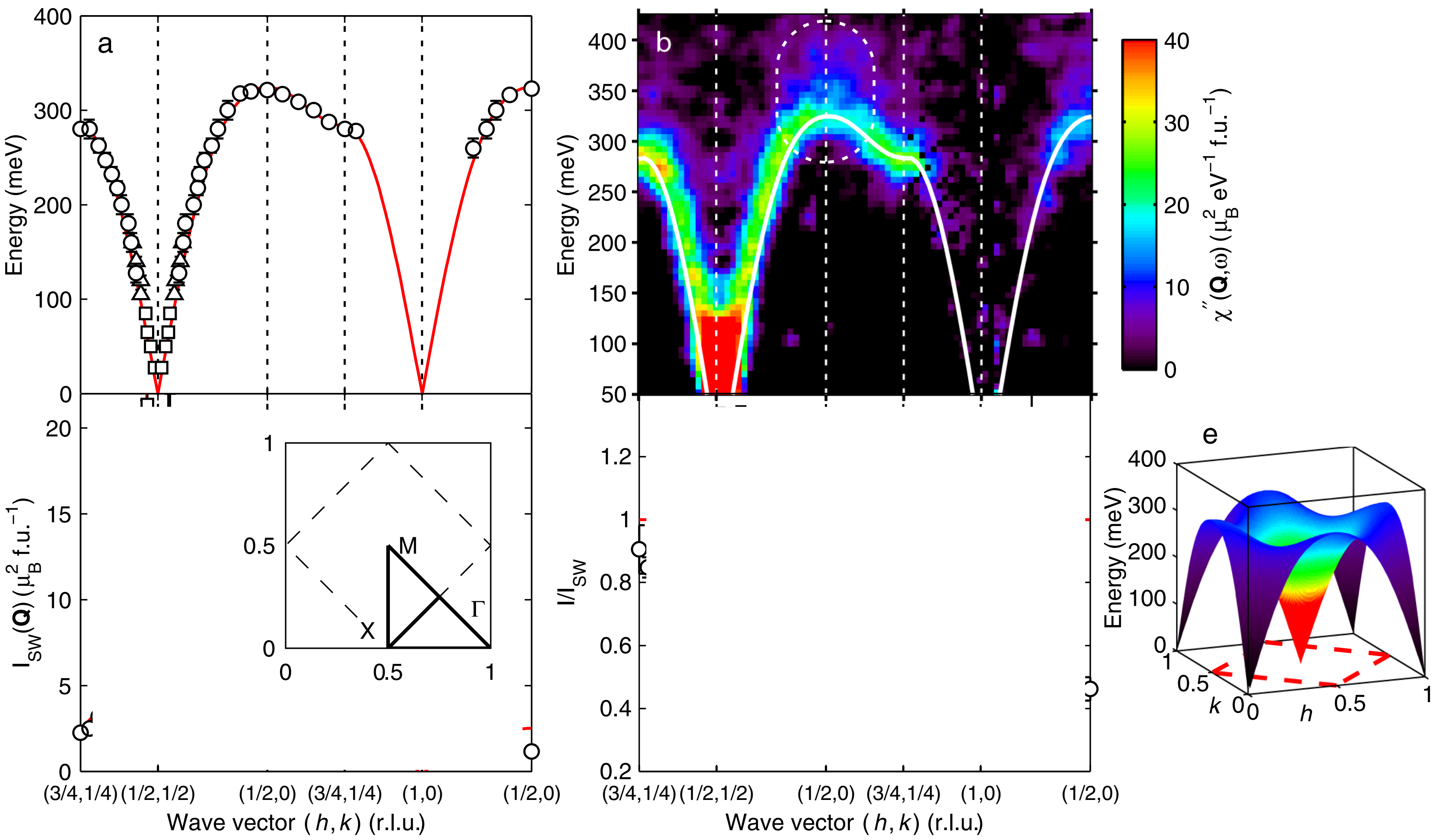
Why does Aluminium not have any acoustic modes?

# Magnons – vibrations of spin





# Magnons – dispersion of $La_2CuO_4$



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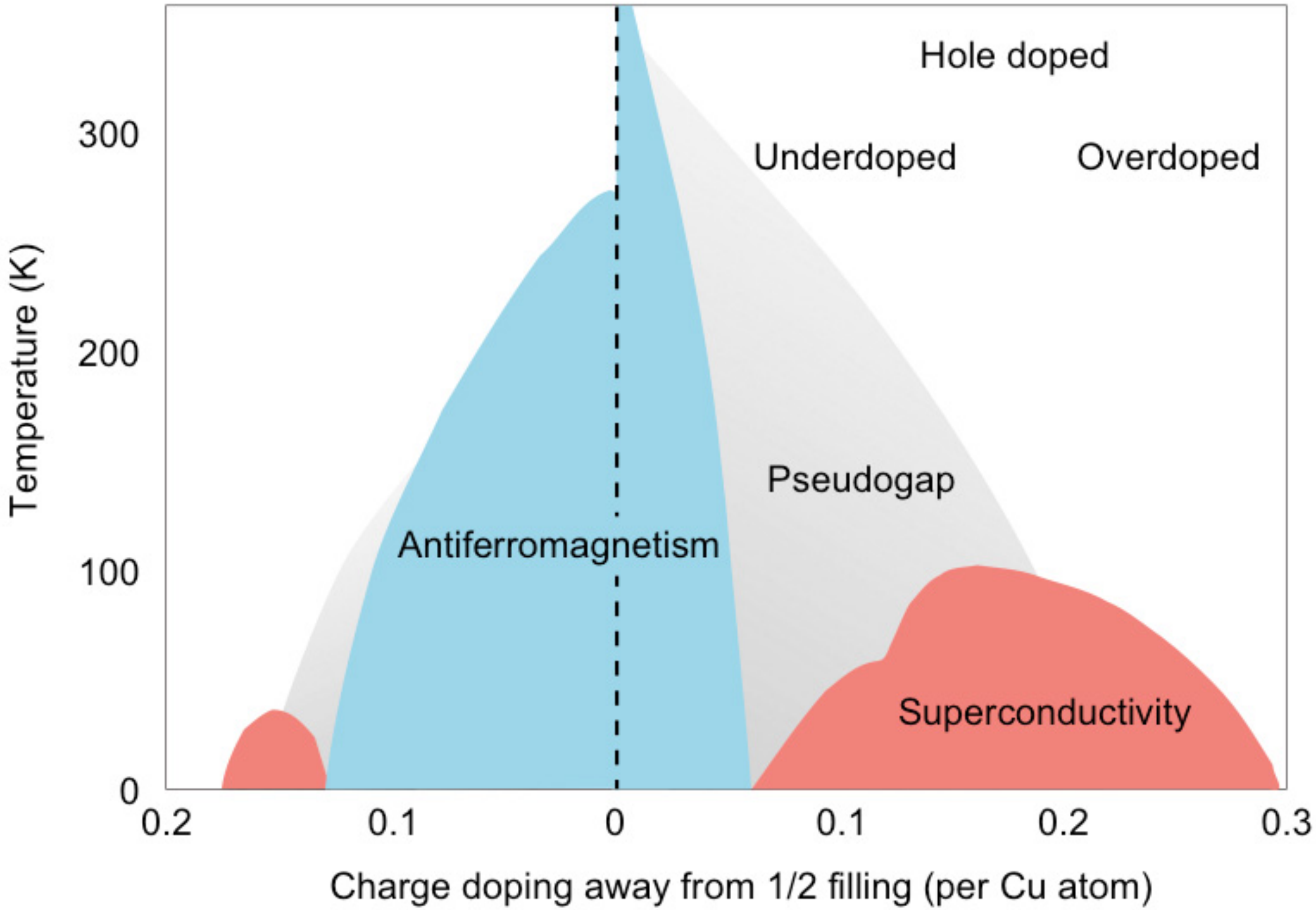
# Doping of materials

**K.A. Müller & G. Bednorz: Discovery of high-temperature superconductivity**
**Nobel Prize 1986**

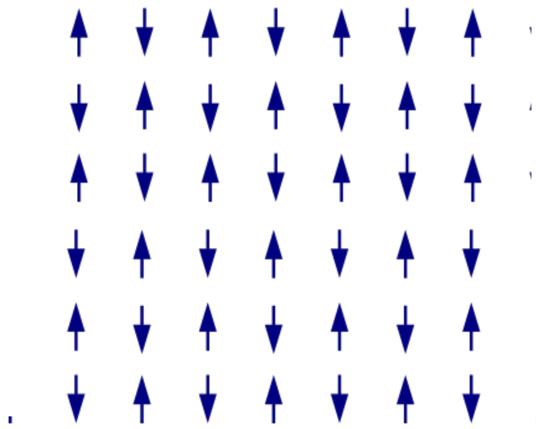
Example:
$La_{2-x}Sr_xCuO_4$
$T_c$ =40 K

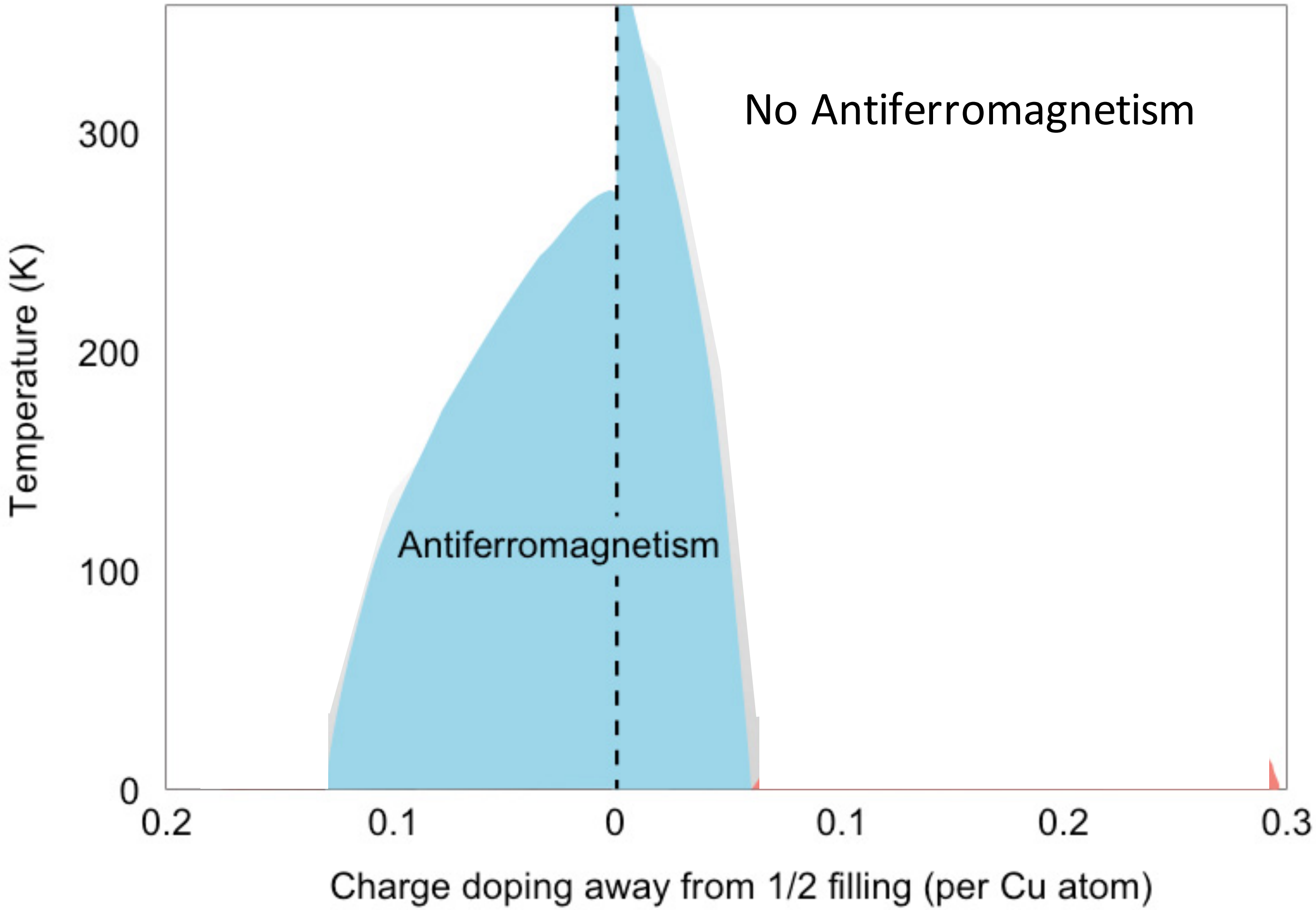
**$La^{3+}$**

**$Sr^{2+}$**

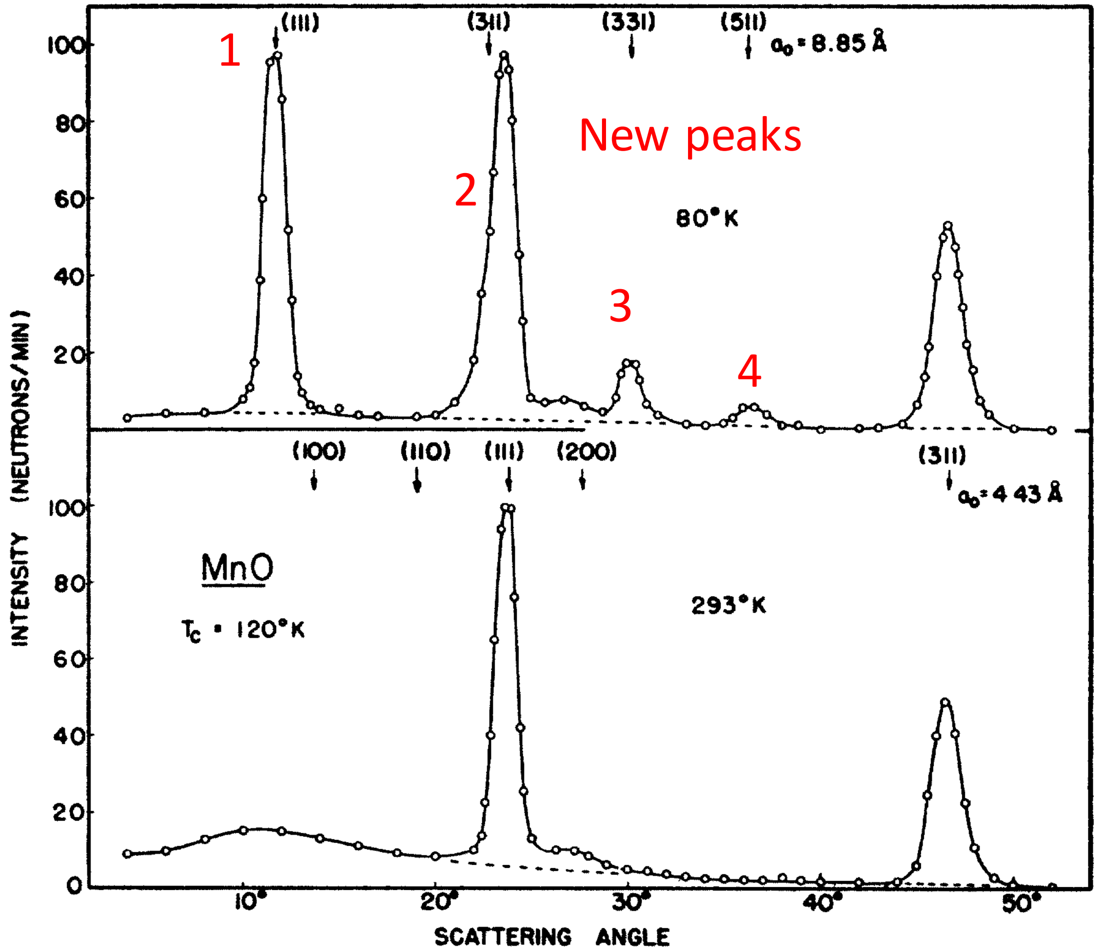


# Phase diagram





# Scattering theory: Structure Factor

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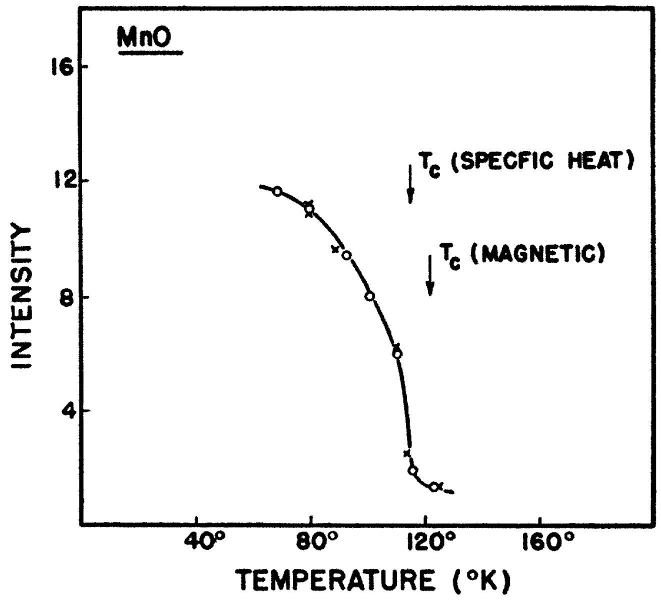
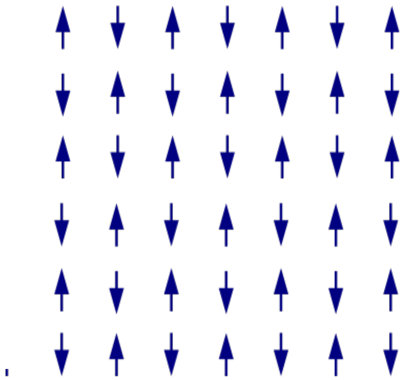
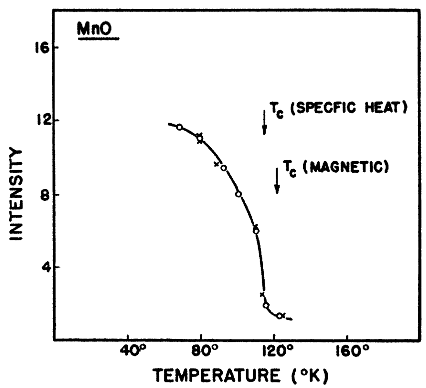
Magnetic phase transition

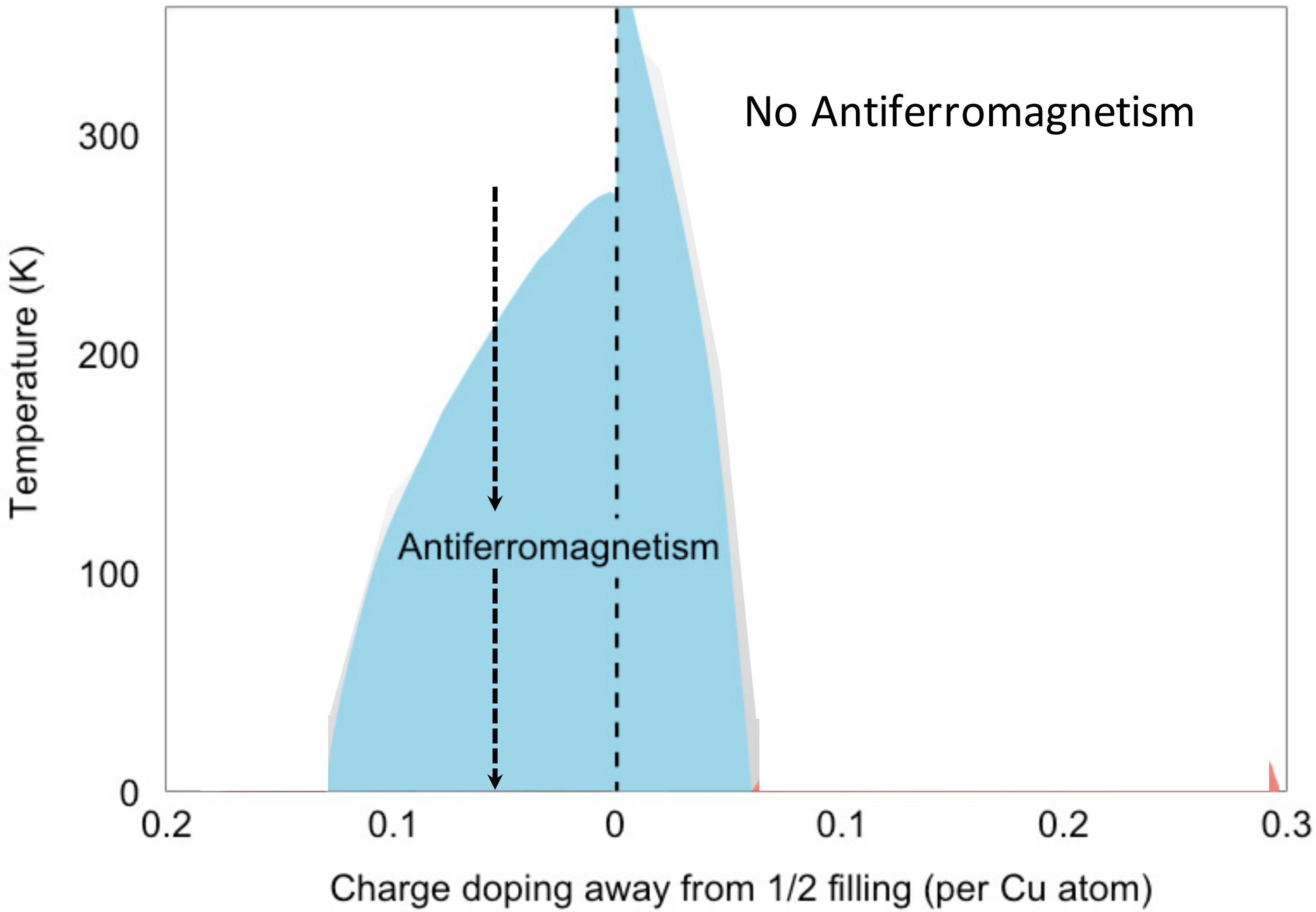



C. G. Shull *et al.*, Phys. Rev. 1951

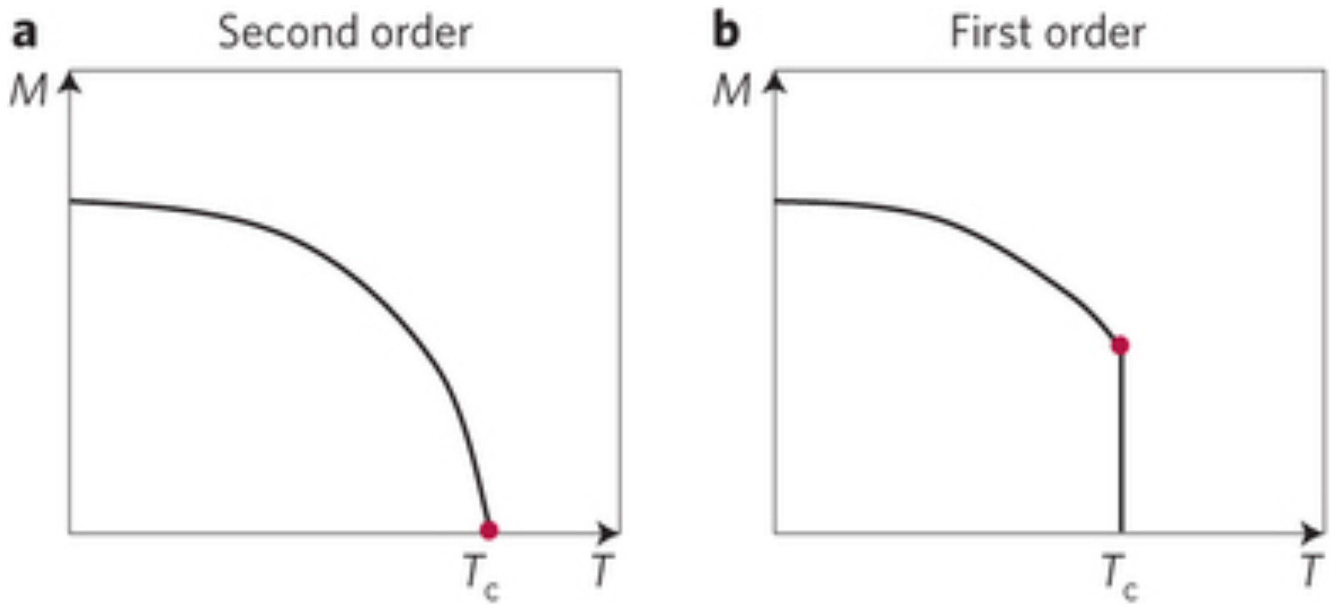
# Magnetic order



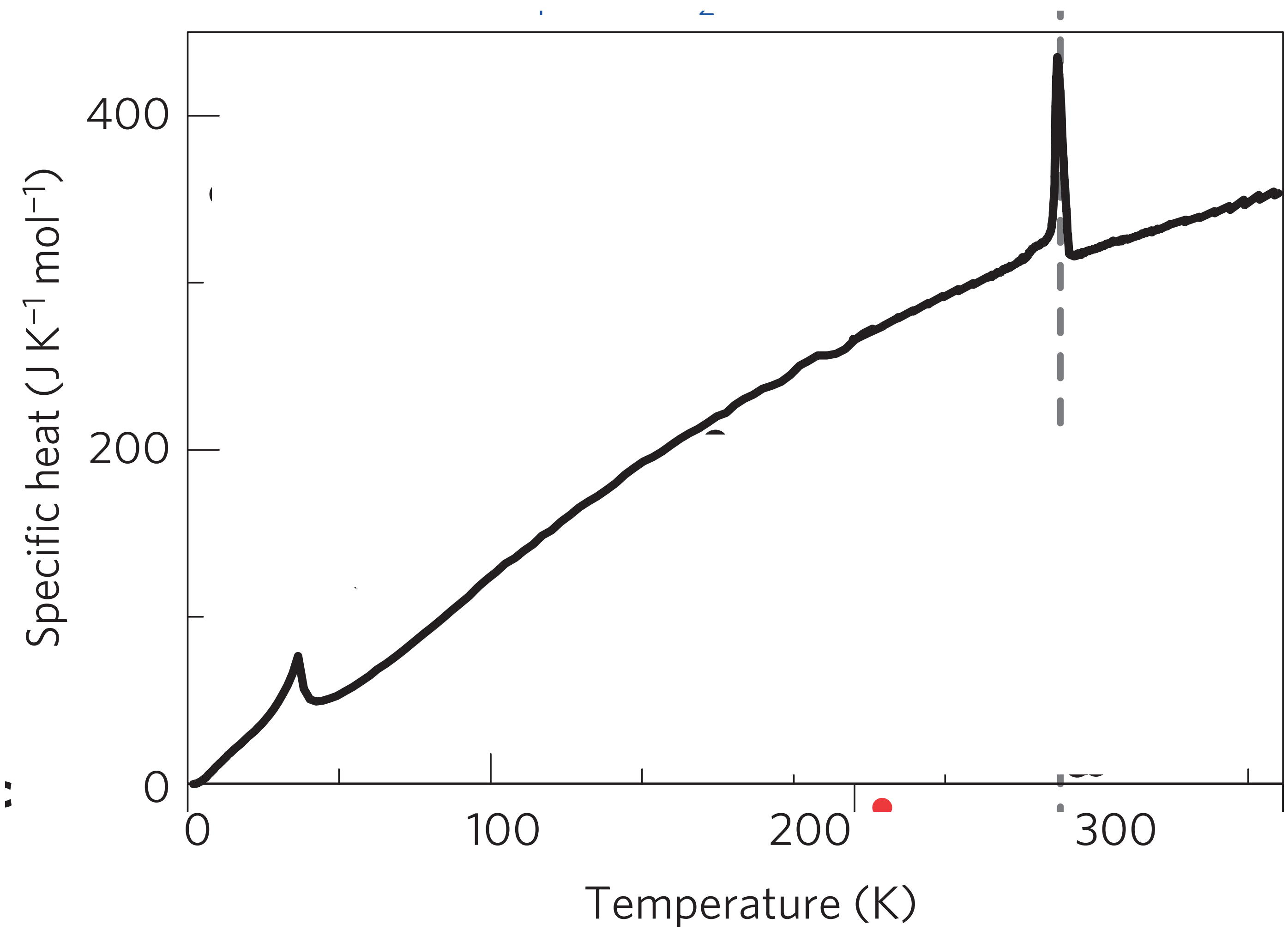


# Order Parameter M

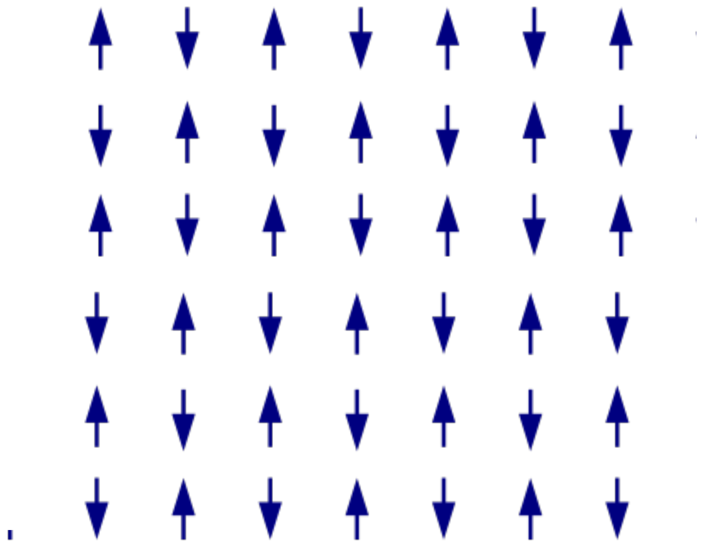


# Heat Capacity and phase transitions




Nat. Mat. **13**, 611 (2014)

# Symmetry breaking



ANTI-FERROMAGNETISM BREAKS TRANSLATIONAL SYMMETRY OF THE CRYSTAL STRUCTURE.

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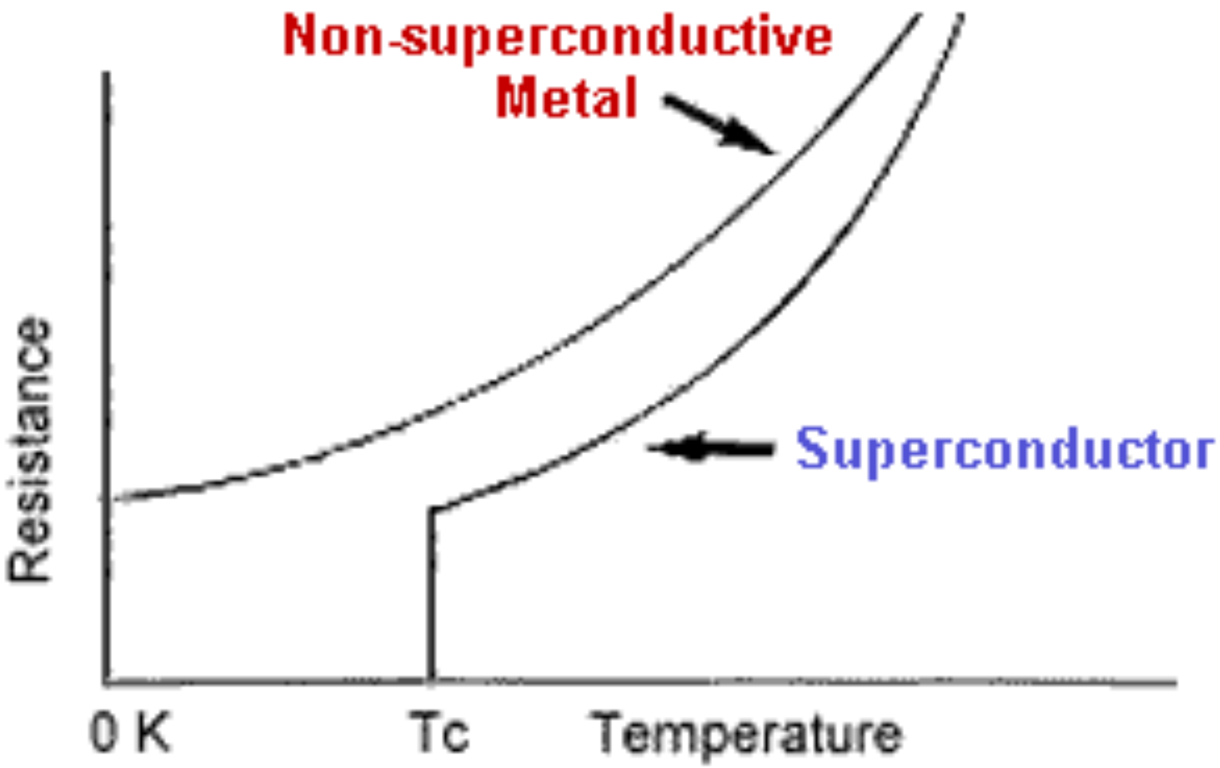
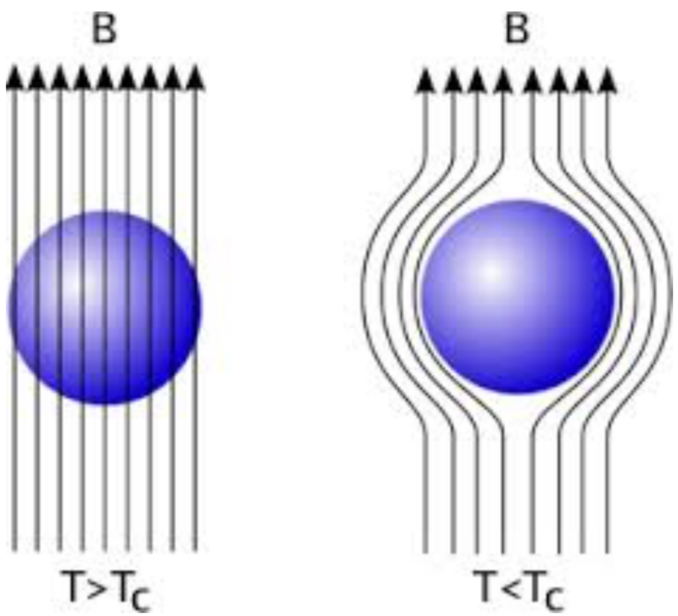
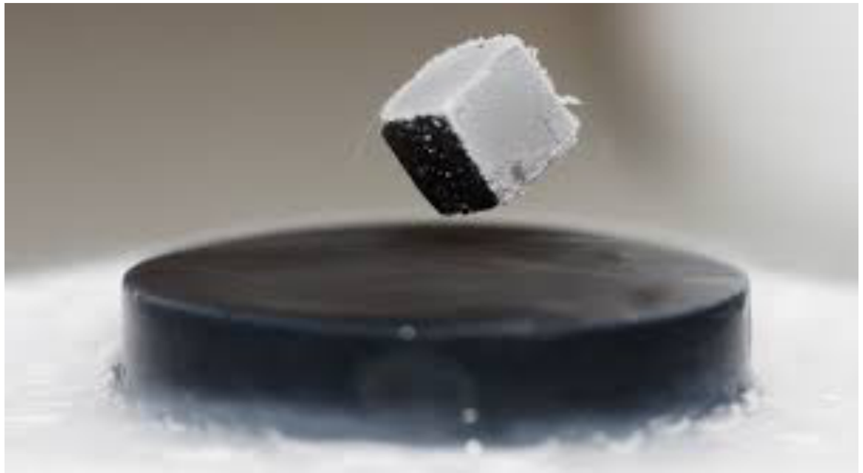
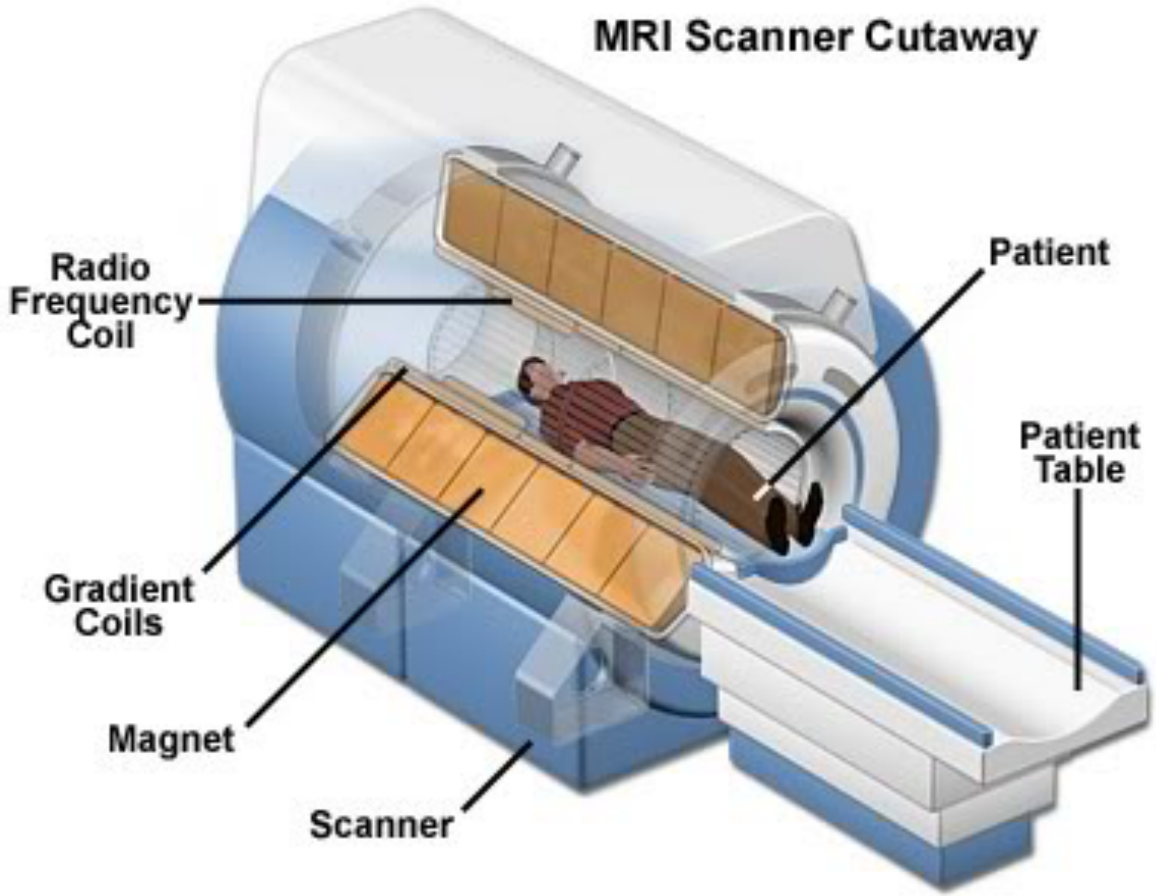
# Superconductivity



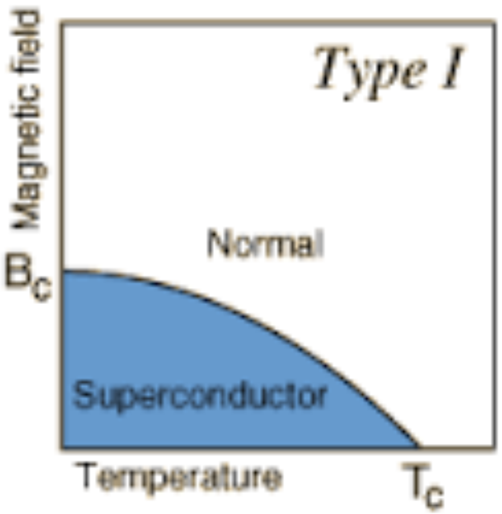
# Meisner effect

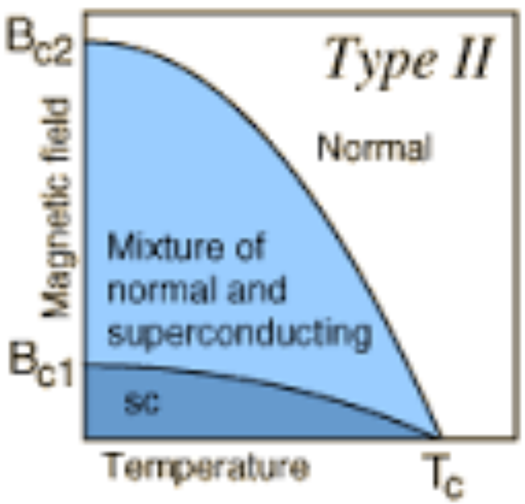


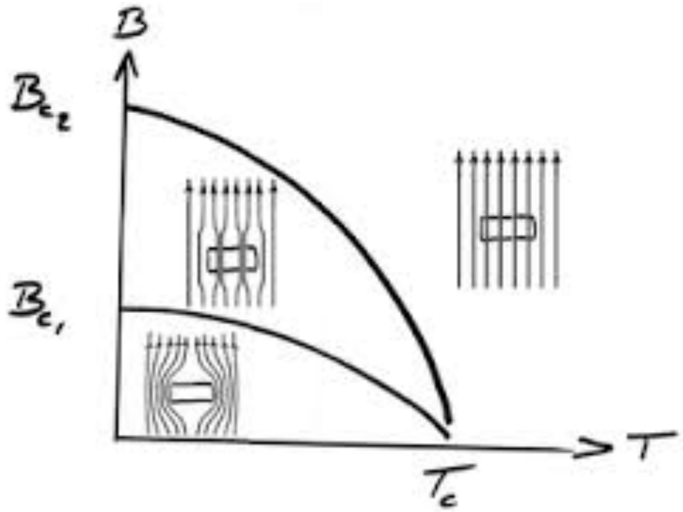




MRI Scanner Cutaway
Radio Frequency Coil
Patient
Patient Table
Gradient Coils
Magnet
Scanner

# Two types of Superconductors

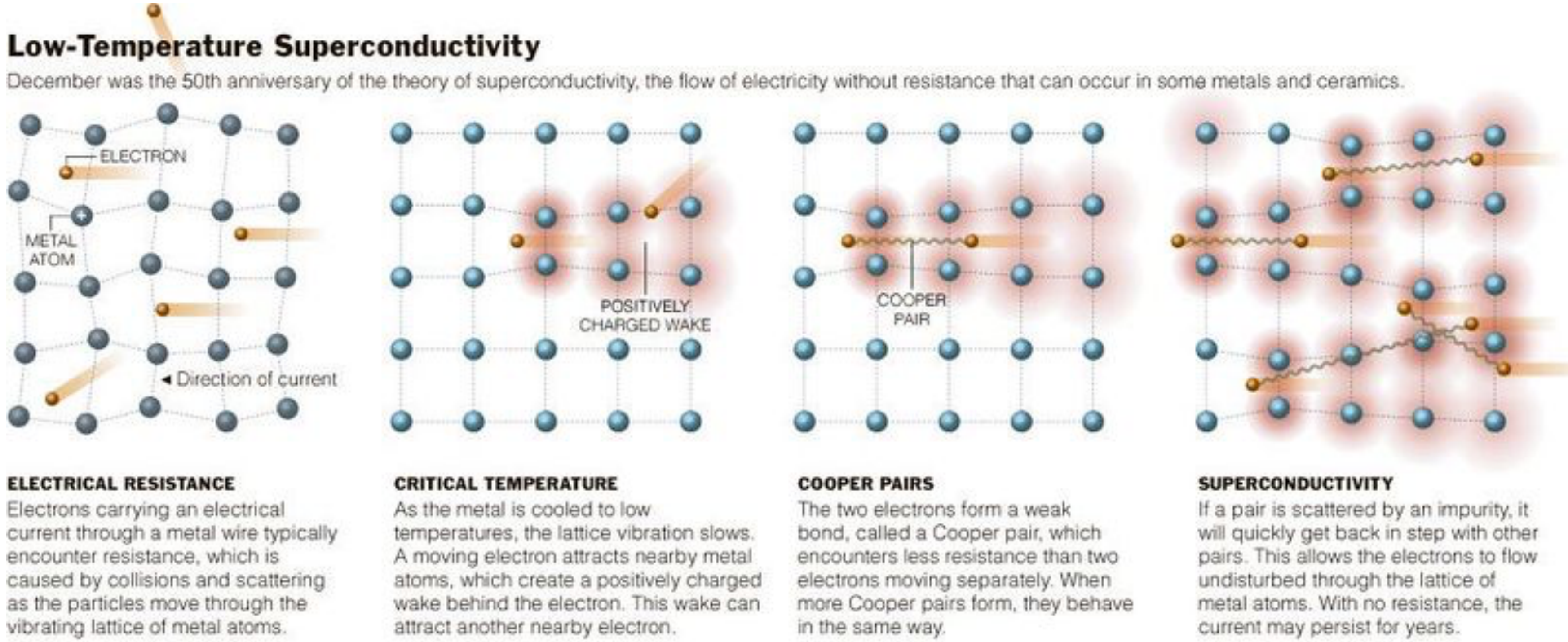


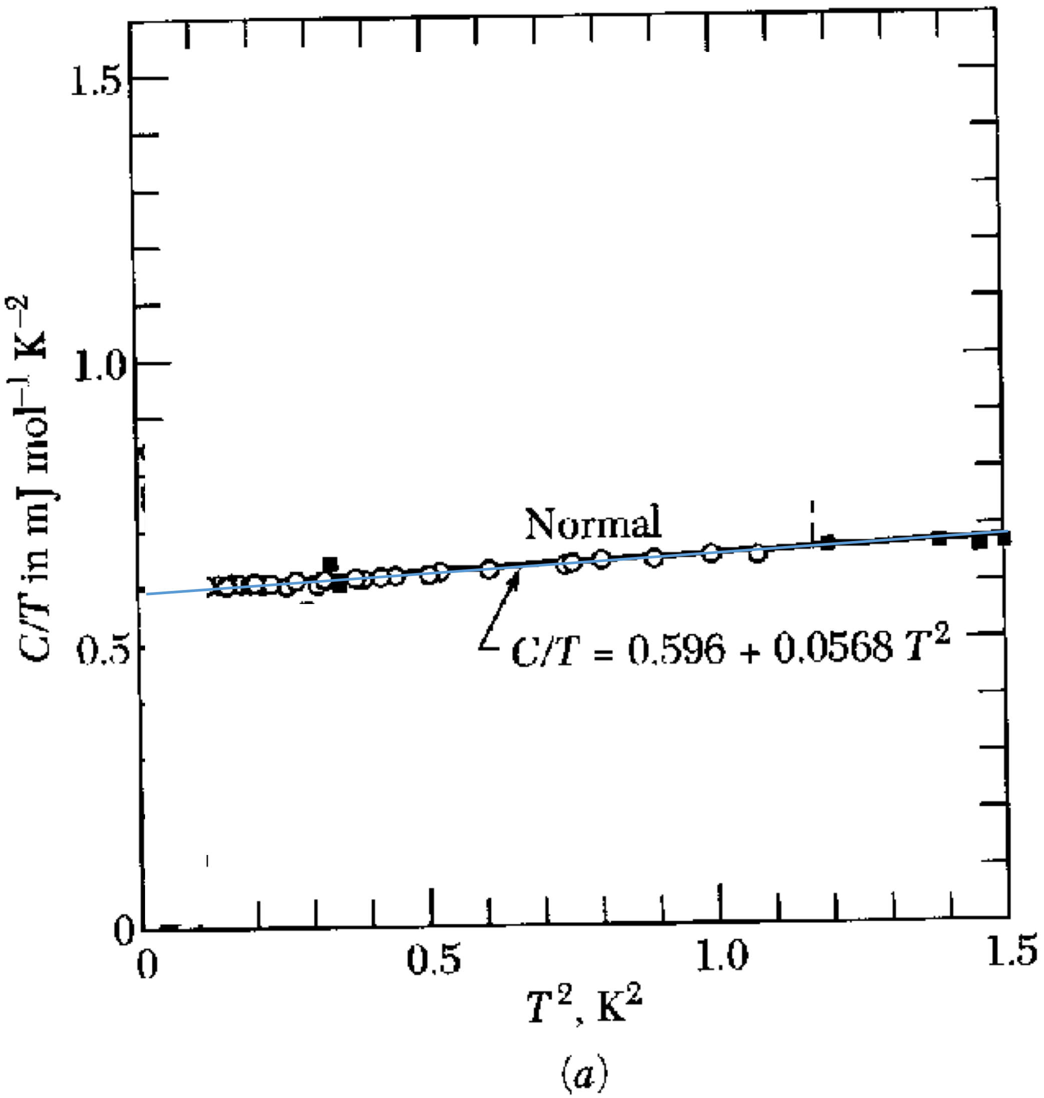
# BCS-Theory of Superconductivity

Bardeen–Cooper–Schrieffer **theory**
(named after John Bardeen, Leon Cooper, and John Robert Schrieffer)



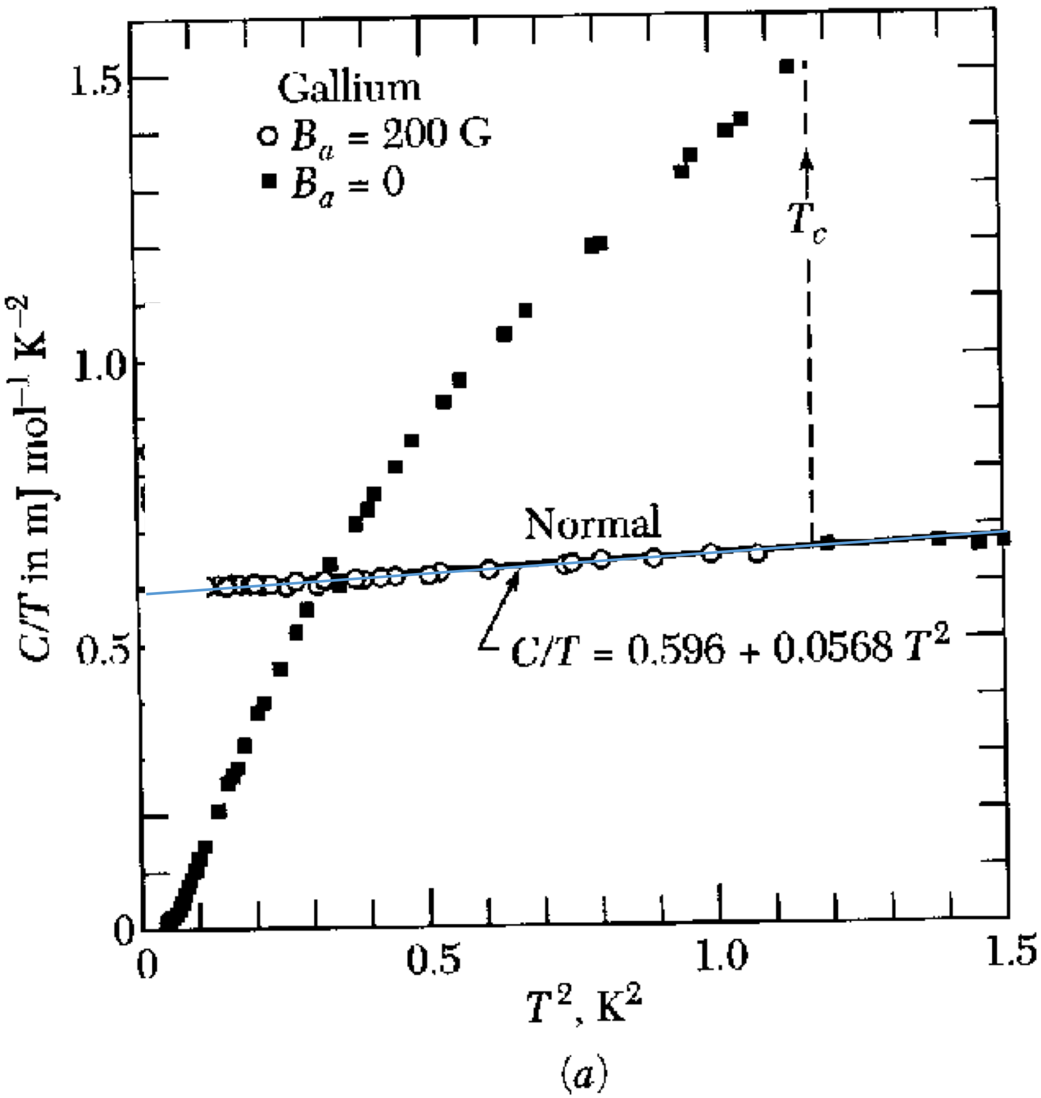

$$\psi = \Delta\, e^{-i\varphi}$$

# Heat capacity




Gallium @ Magnetic field 200 Gauss

# Heat capacity




Gallium @ Magnetic field 200 Gauss

# Density of states

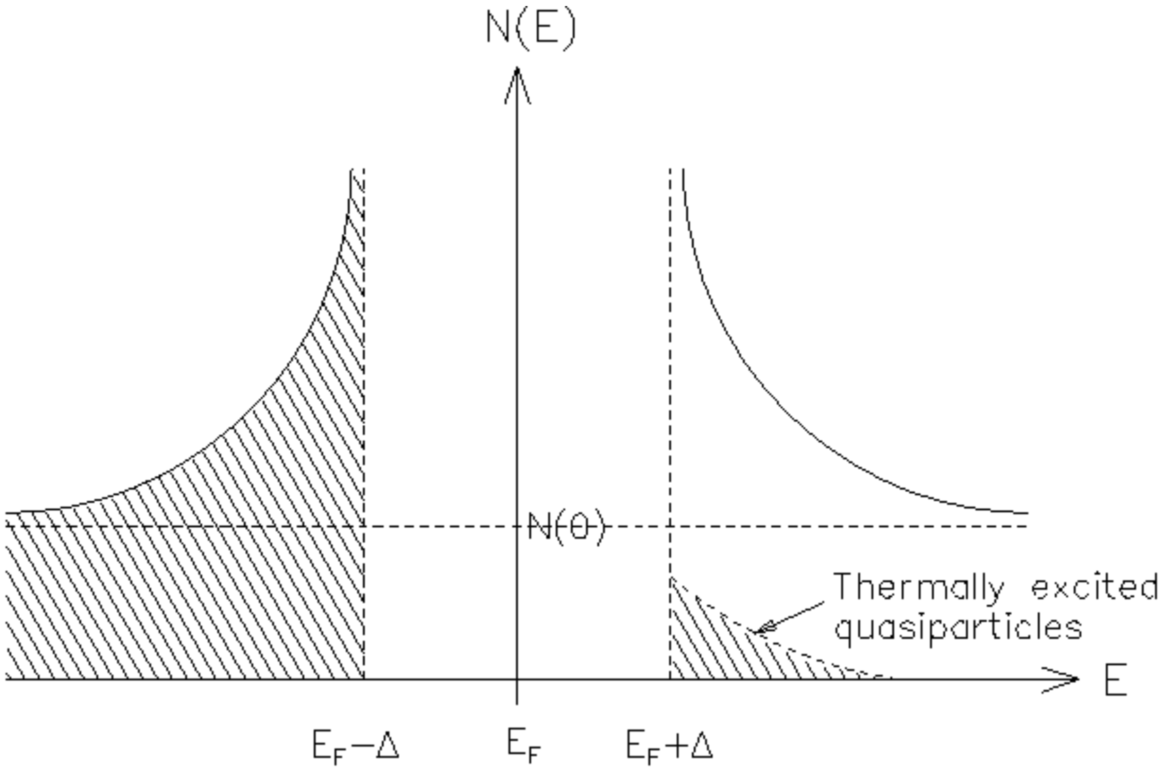
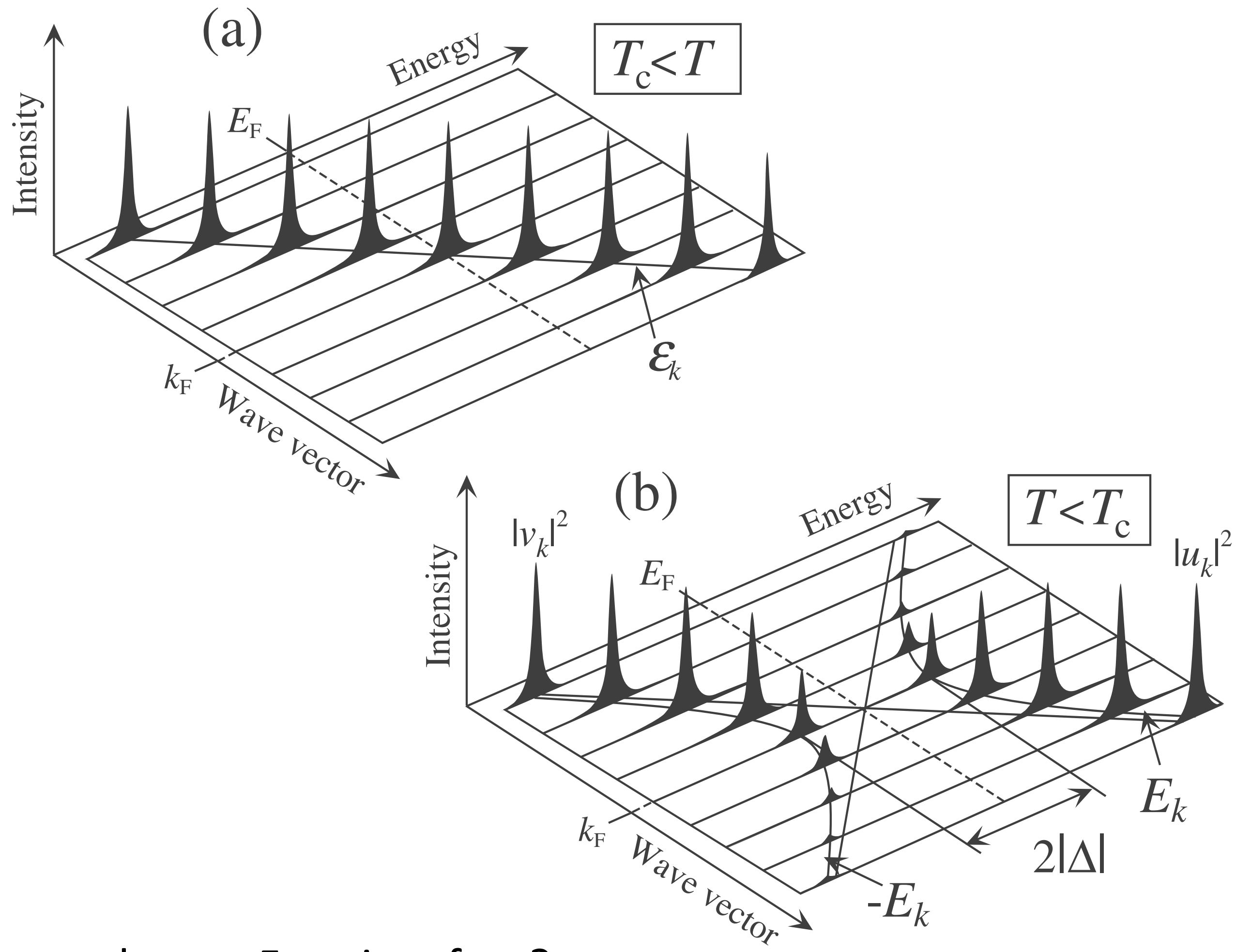


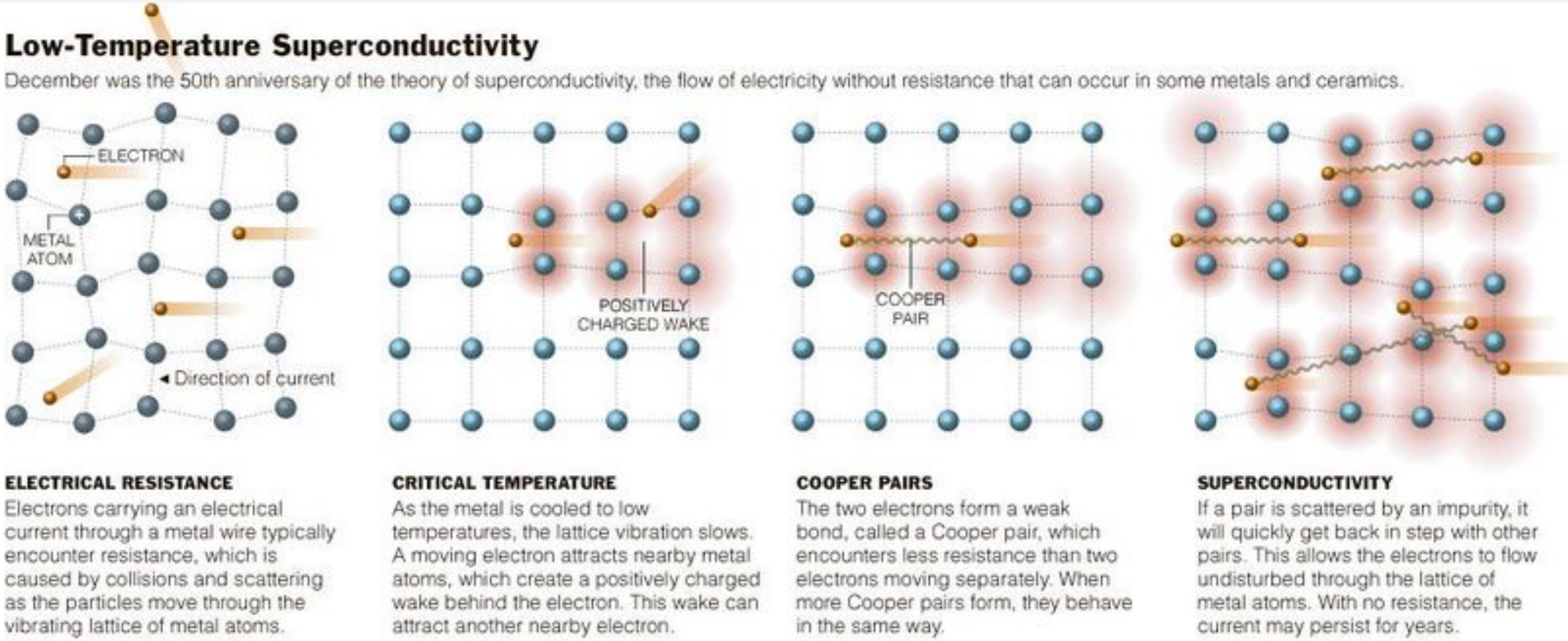

Figure 2.7: The density of states for a BCS superconductor at $T > 0$ K. As $T$ is increased above absolute zero, Cooper pairs are broken and the resulting normal electrons occupy states above $E_F + \Delta$ .

# Superconducting gap




Does a superconductor have a Fermi surface?

# BCS-Theory predictions



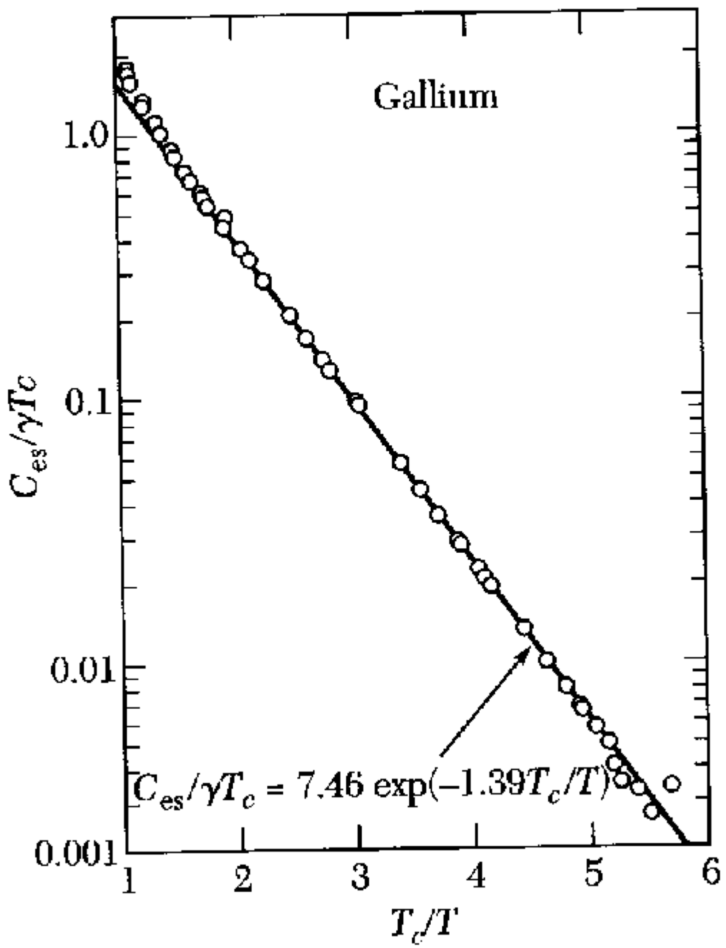

(1) A superconducting gap was predicted.

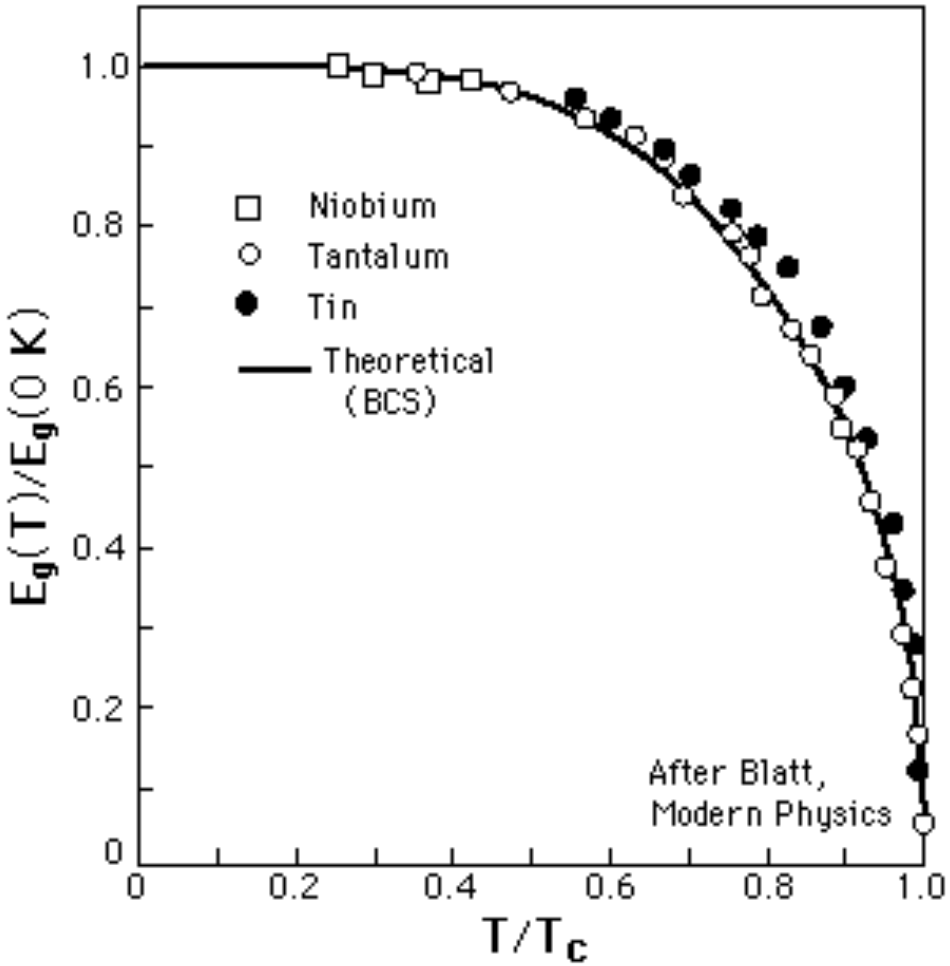
(2) $\Delta\,(0) = 1.7 k_B\, T_c$

(3) Heat capacity: $C \sim e^{\frac{-\Delta}{k_B T}}$

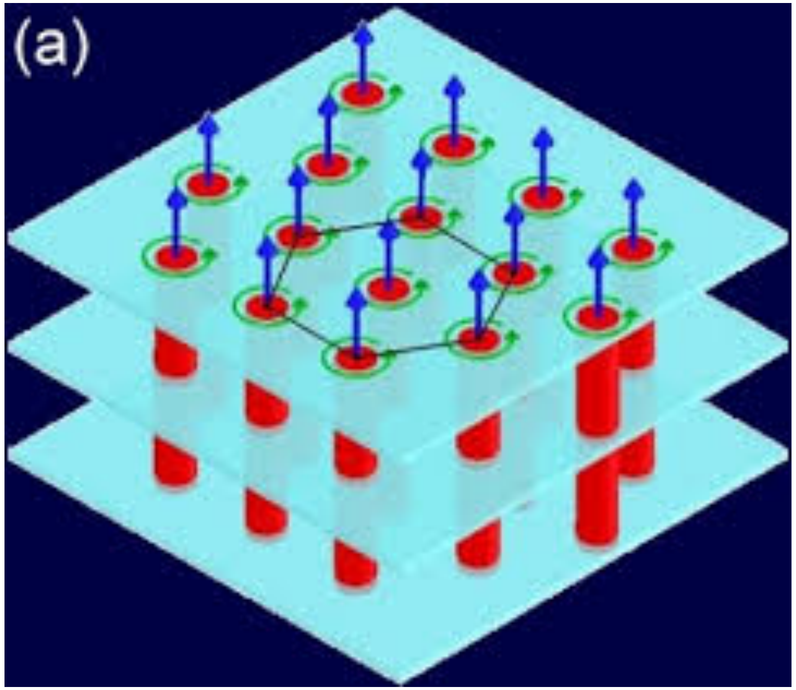
(4) $\Delta\,(T \rightarrow T_c) = \frac{3\,k_B T_c}{\sqrt{T_c}}\sqrt{T_c - T}$

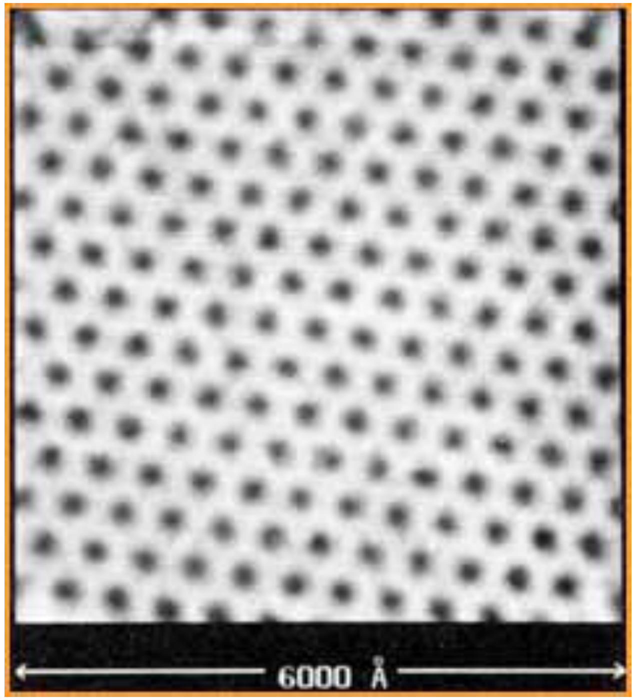
# Predictions vs Experiment



# Vortex lattice




Superconducting coherence length (= core size):

$$\xi = \frac{\hbar v_F}{\pi \Delta}$$