

# 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

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End Exam

5 min - evaluation

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

### **MY AVAILABILITY BEFORE EXAM:**

30<sup>th</sup>-31<sup>th</sup> May

1<sup>st</sup> and 6<sup>th</sup> of June

johan.chang@physik.uzh.ch

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## Exam information

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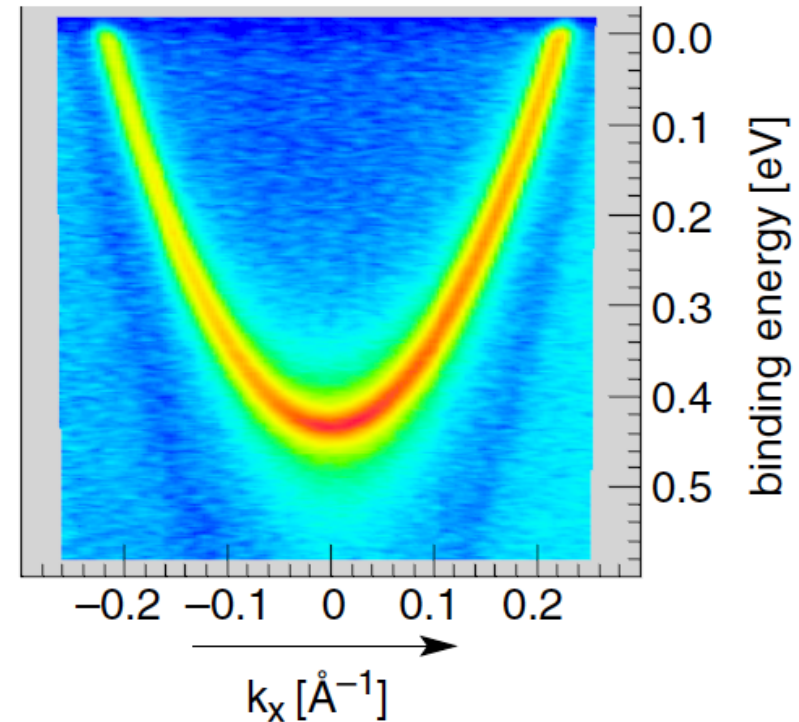
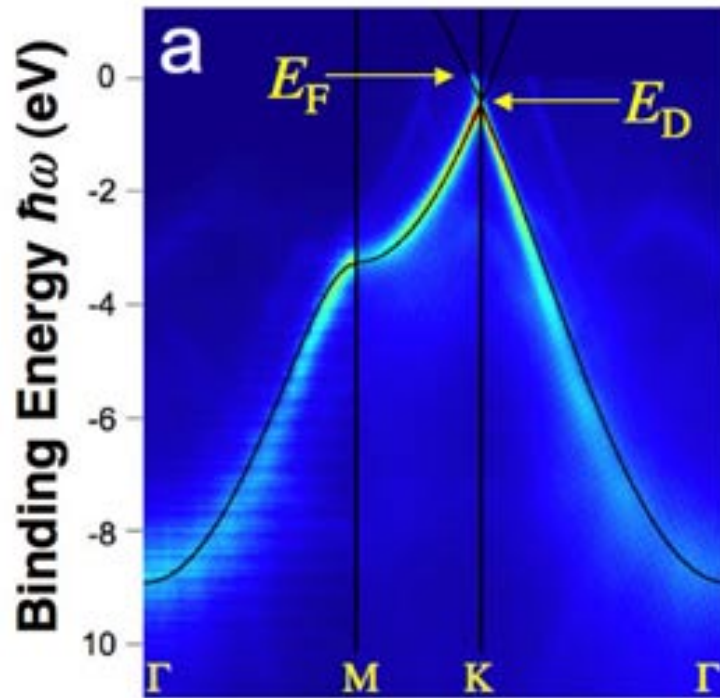
Landau theory

## Superconductivity

Intro & applications

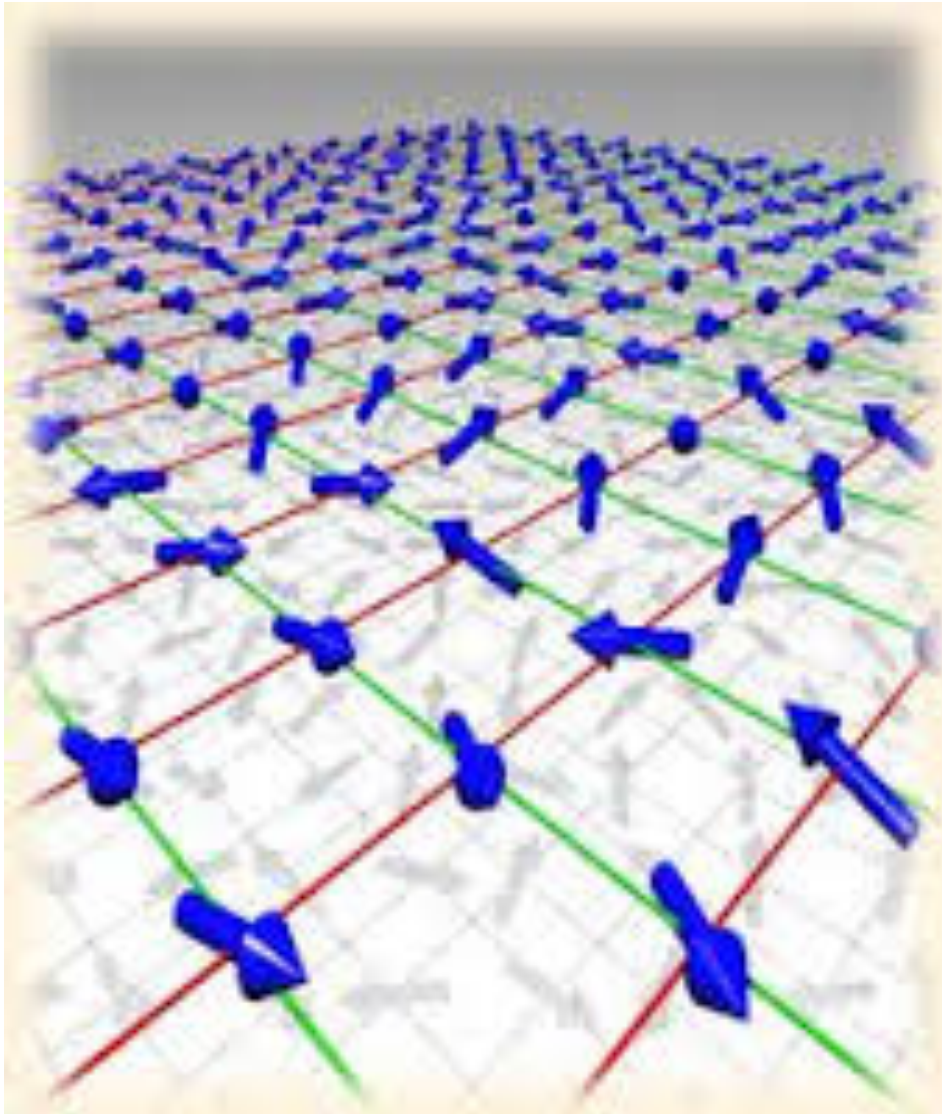
Specific heat

# 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

$$U = -JS_i \cdot S_j$$

Nearest Neighbor Interaction

$J$  = "Coupling between spins"

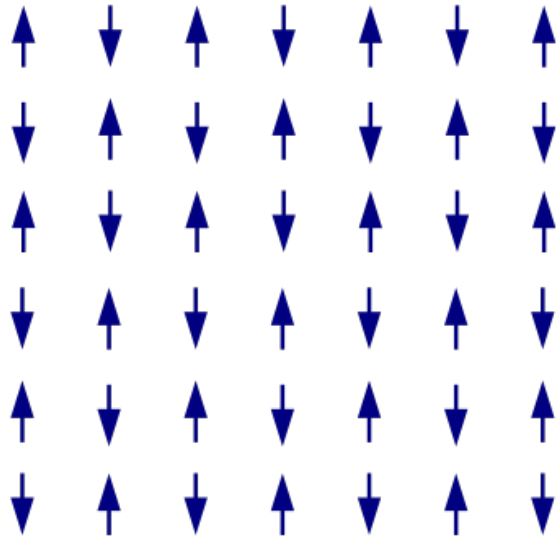
Nature likes to minimize the energy  $U$ !

# Heisenberg Model

$$U = -JS_i \cdot S_j$$

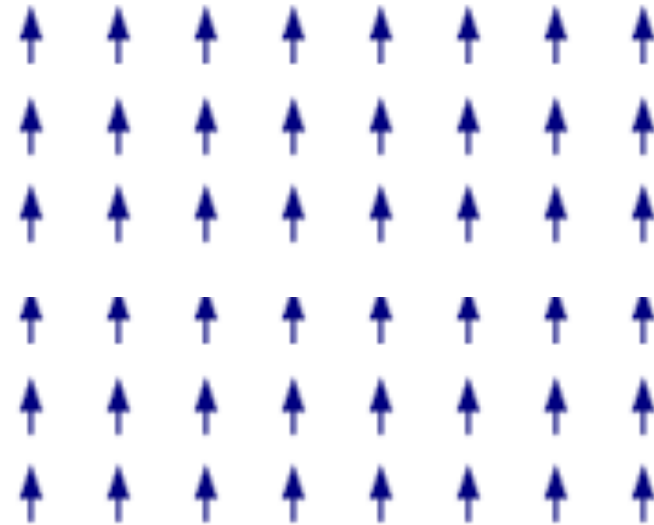
**Anti-ferromagnetism**

**$J < 0$**



**Ferromagnetism**

**$J > 0$**

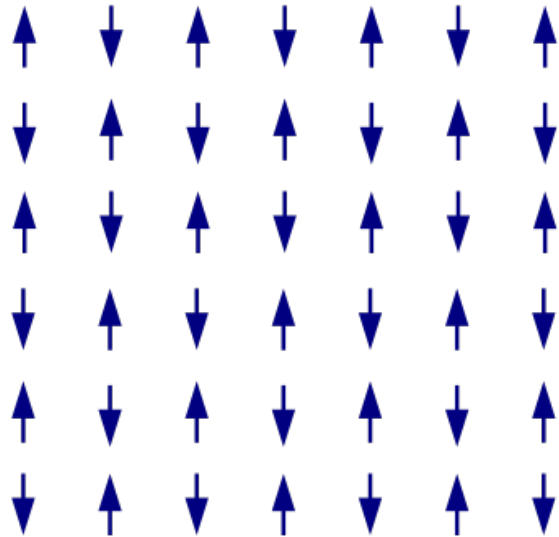


# Heisenberg Model

$$U = -JS_i \cdot S_j$$

**Anti-ferromagnetism**

**$J < 0$**



1. What is the lattice parameter?

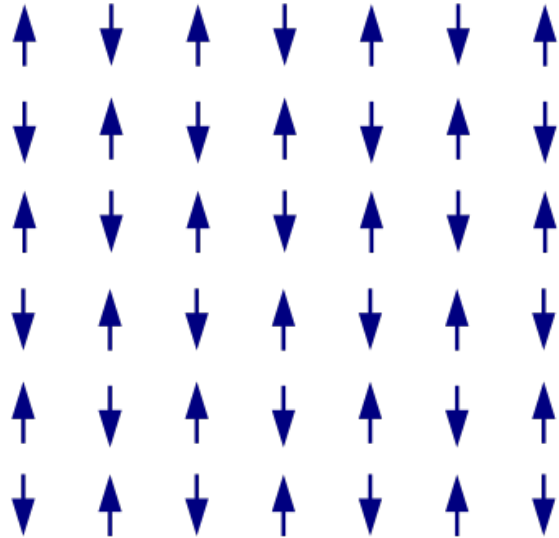
2. What happens to the unit cell?

3. What about the first Brillouin zone?

# Scattering theory: Magnetic Form Factor

**Anti-ferromagnetism**

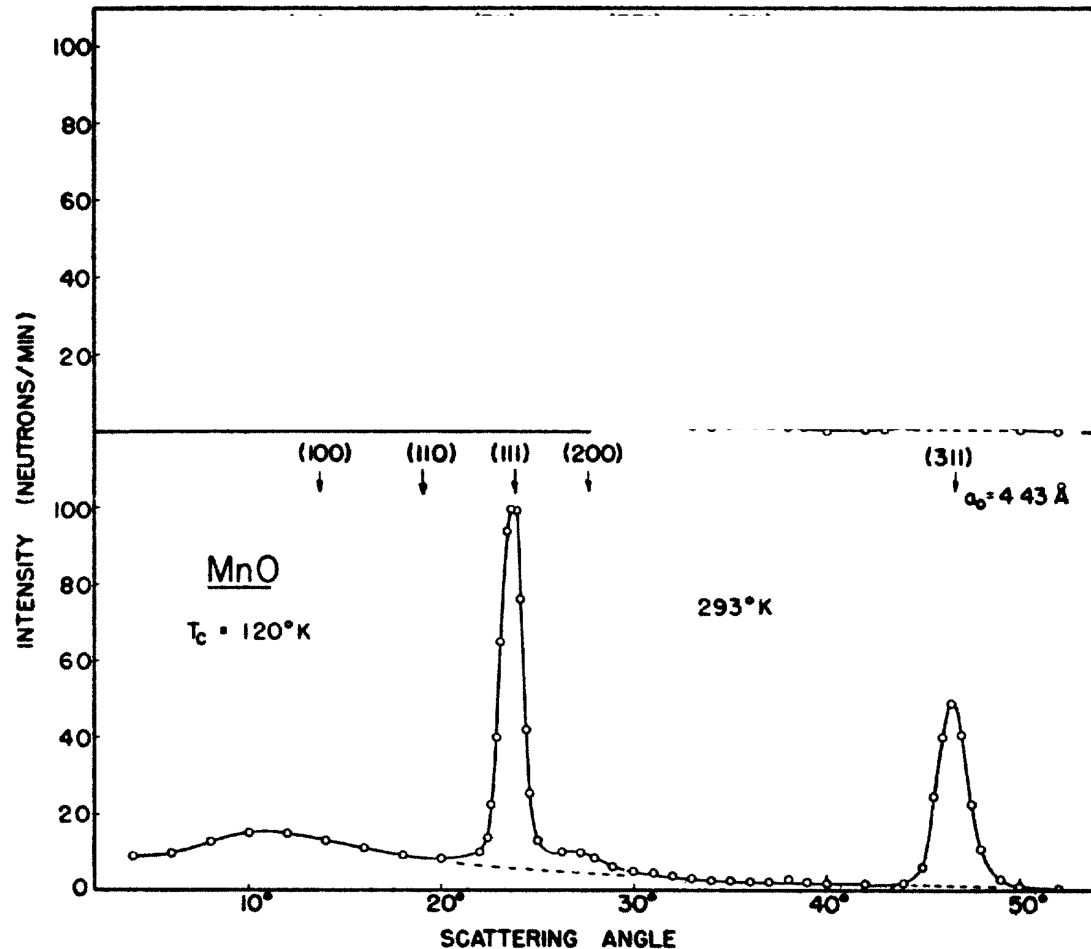
$J < 0$



What is your expectation for the magnetic form factor?



# Scattering theory: Structure Factor



Example: MnO

Atomic crystal lattice

NaCl – type structure

$$S = 4 (f_M - f_O) \text{ when } hkl \text{ even}$$

$$S = 4 (f_M + f_O) \text{ when } hkl \text{ odd}$$

$$S = 0 \text{ mixed parity}$$

$$f_M \sim -f_O$$

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.

# Scattering theory: Structure Factor

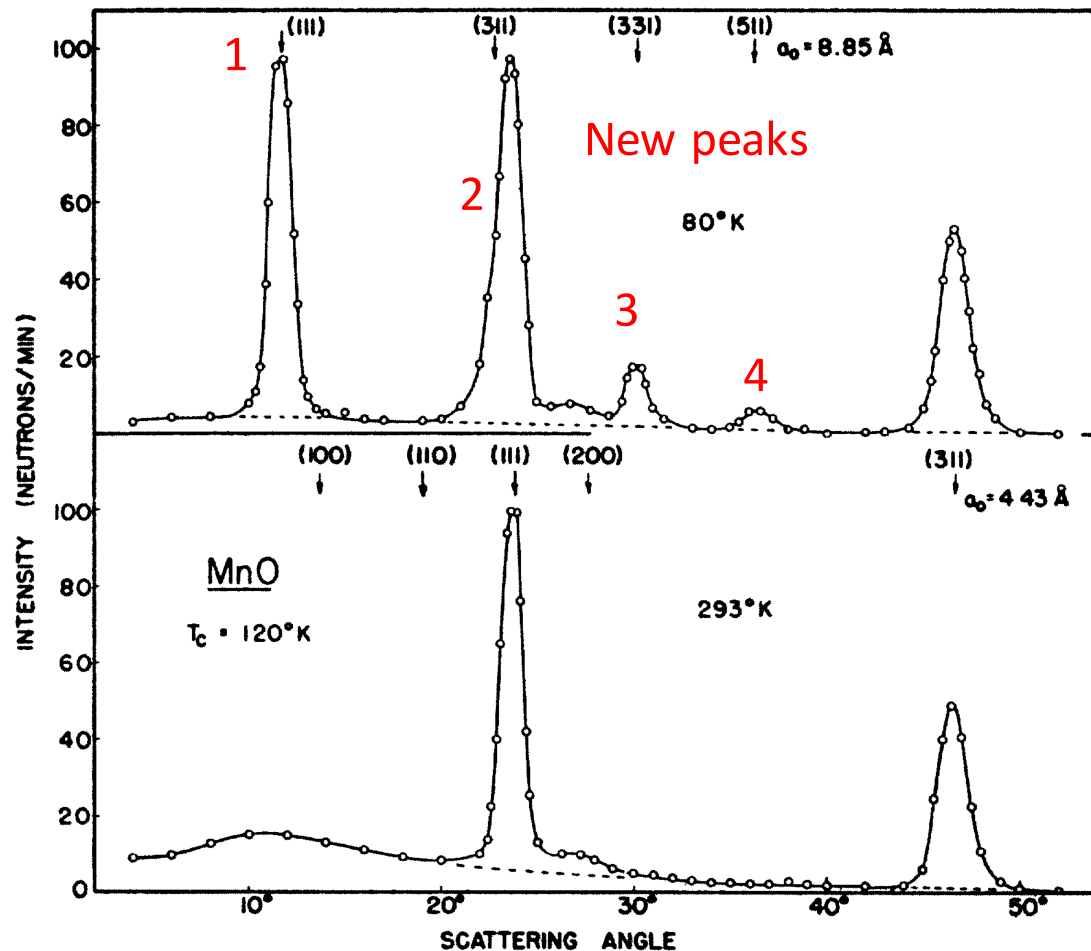


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

Magnetic "Crystal" structure can be resolved.

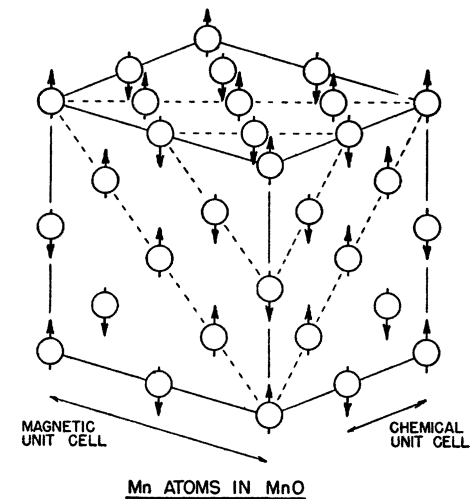
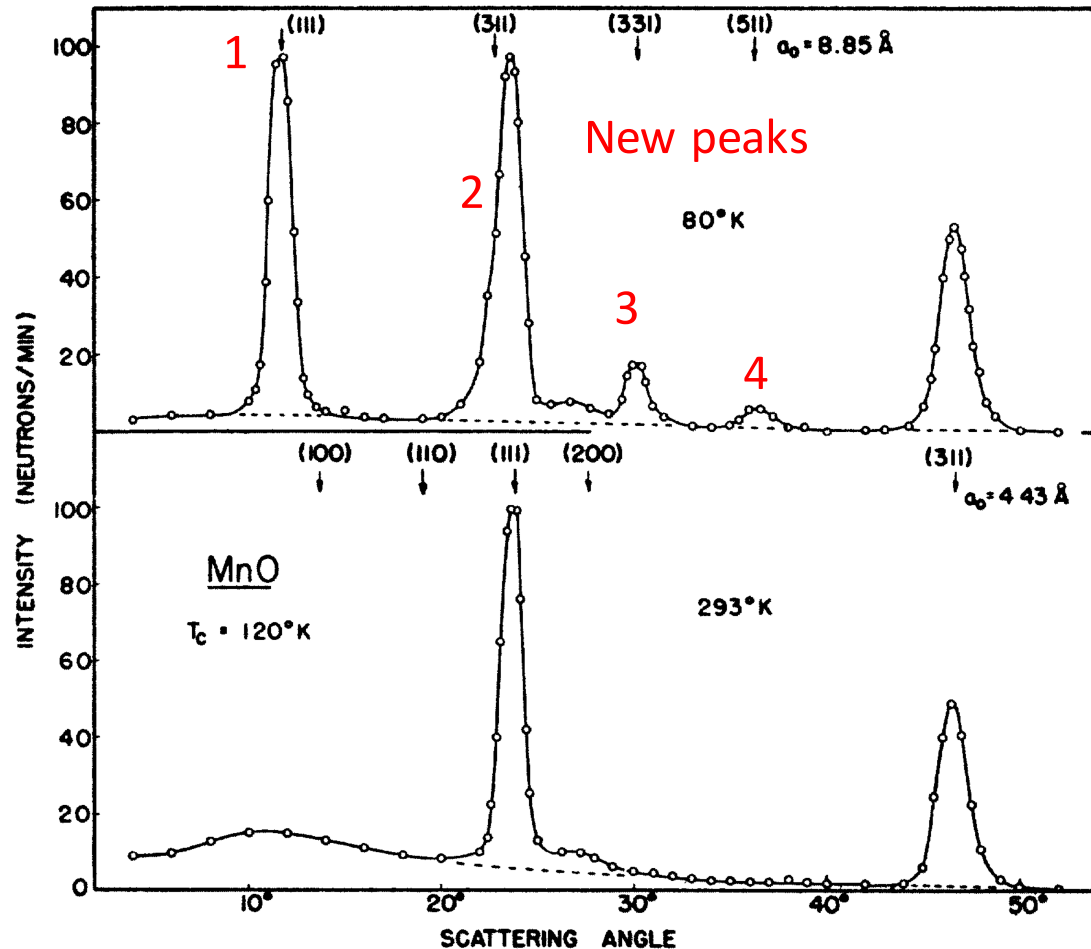


FIG. 5. Antiferromagnetic structure existing in MnO below its Curie temperature of  $120^\circ \text{ K}$ . The magnetic unit cell has twice the linear dimensions of the chemical unit cell. Only Mn ions are shown in the diagram.

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

# Scattering theory: Structure Factor



Magnetic phase transition

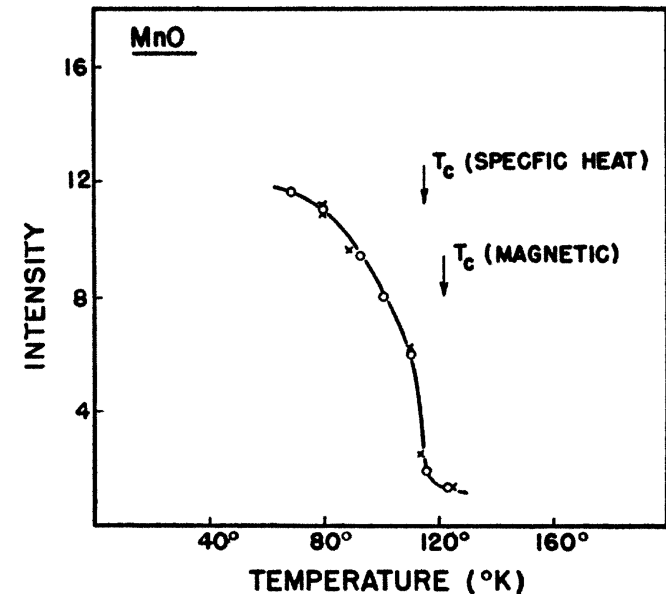
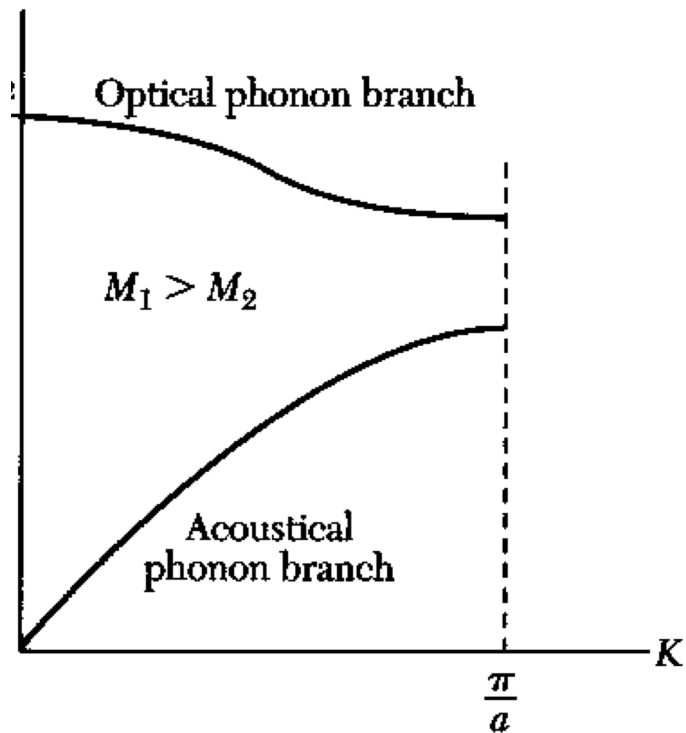


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

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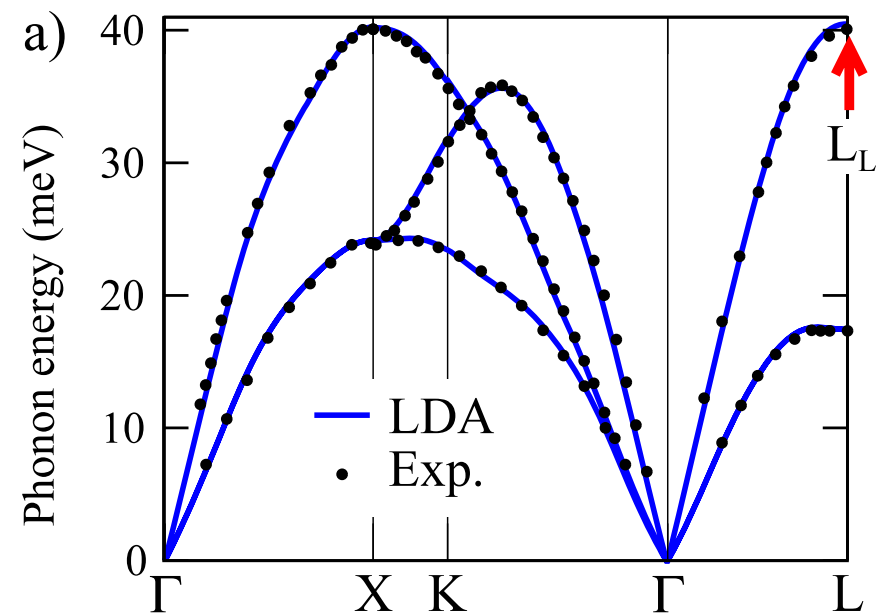
# Phonons – Lattice vibrations

Simple Model Calculation



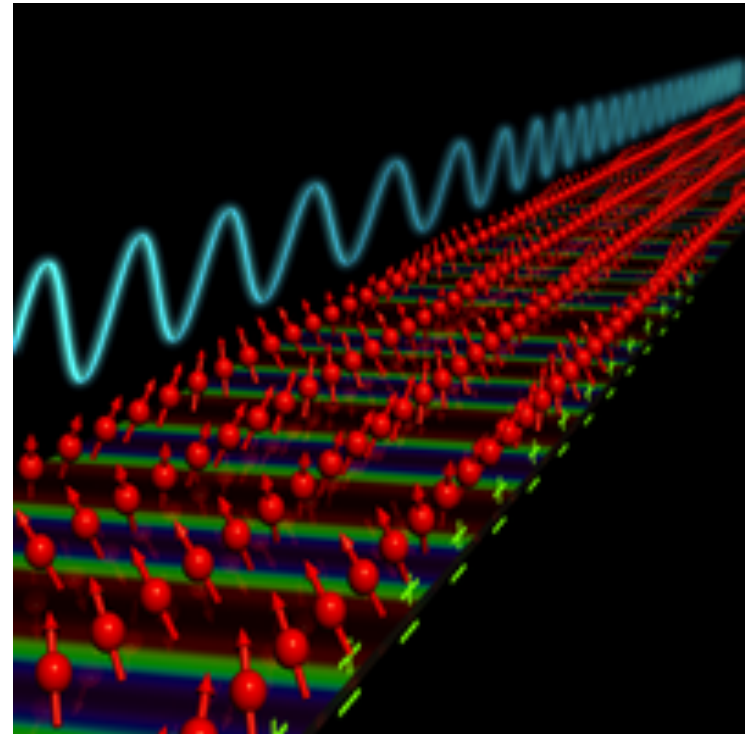
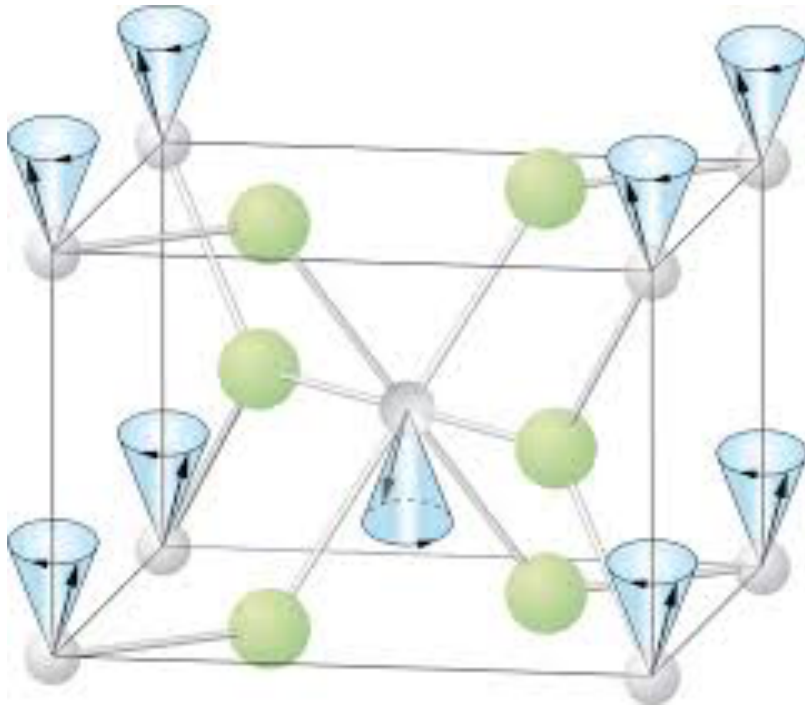
What determines the phonon dispersion at the zone boundary?

Phonons of Aluminium

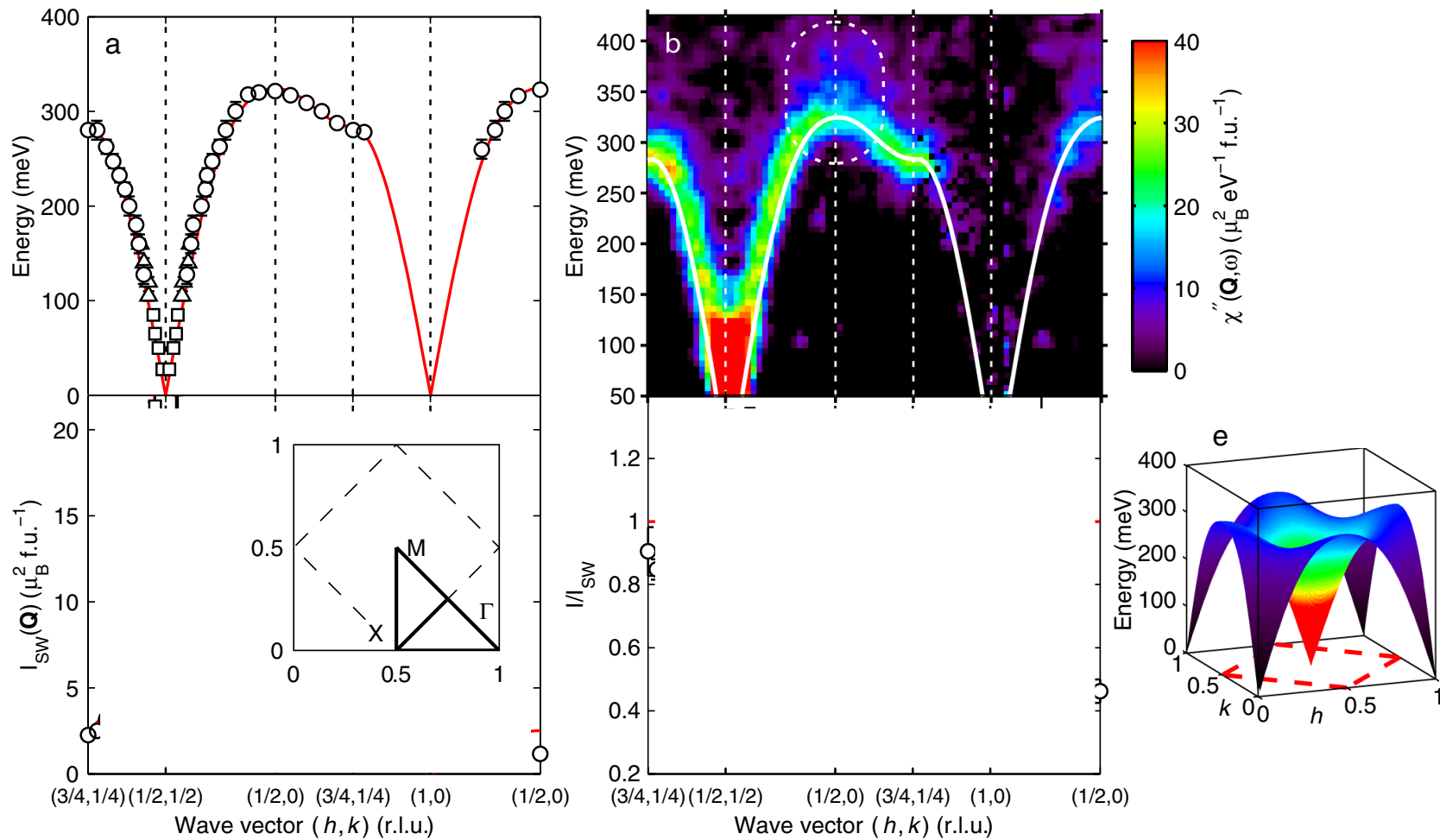


Why does Aluminium not have any acoustic modes?

# Magnons – vibrations of spin



# Magnons – dispersion of $\text{La}_2\text{CuO}_4$



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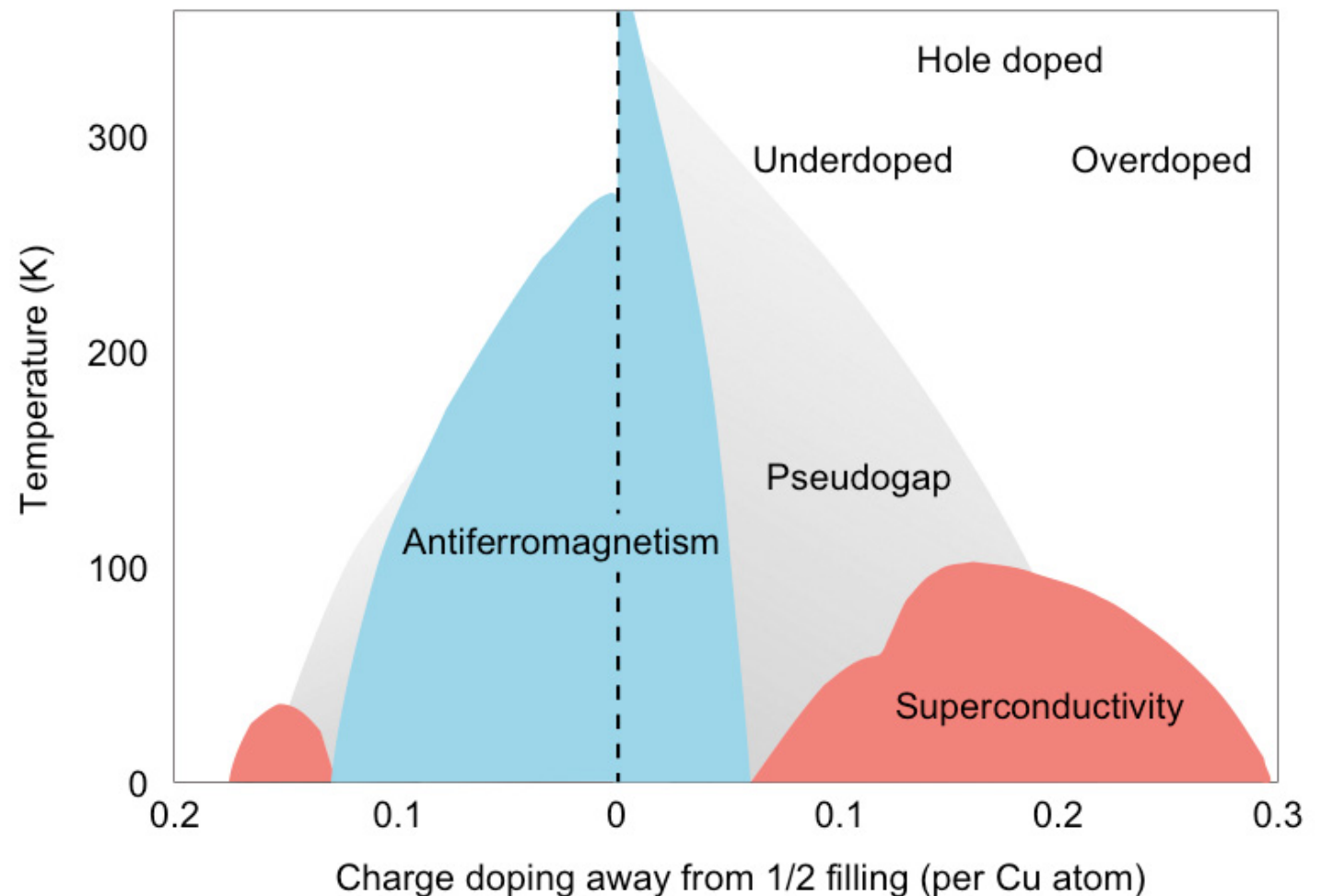
# Doping of materials

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

Example:  
 $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$   
 $T_c = 40 \text{ K}$

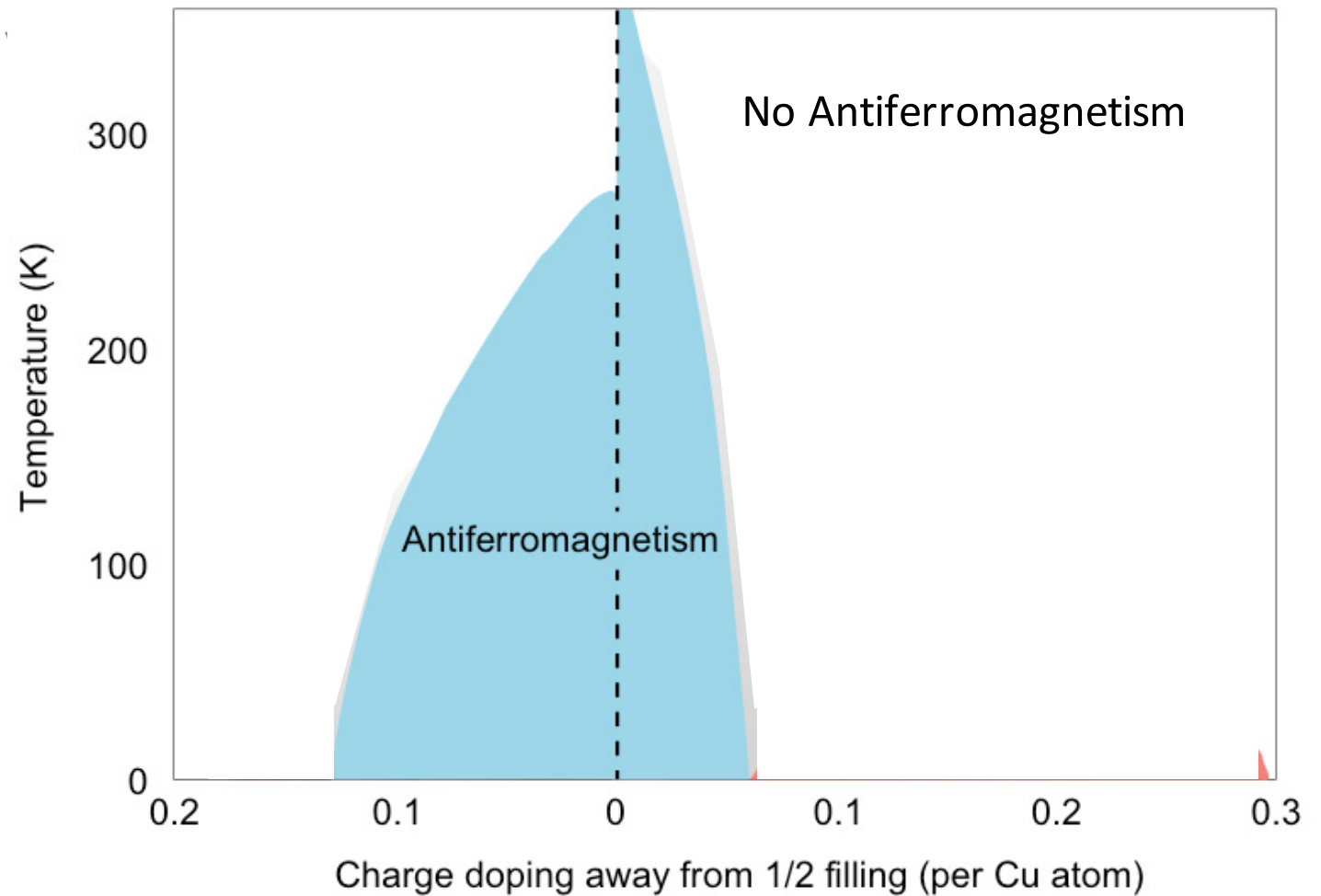
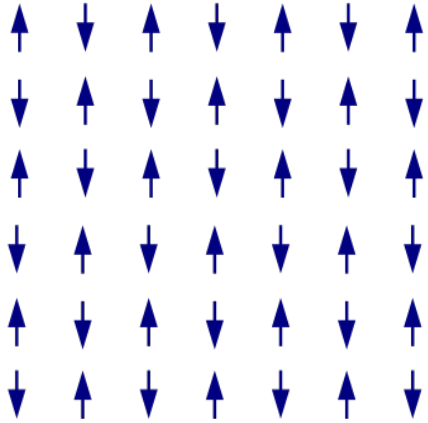
$\text{La}^{3+}$

$\text{Sr}^{2+}$

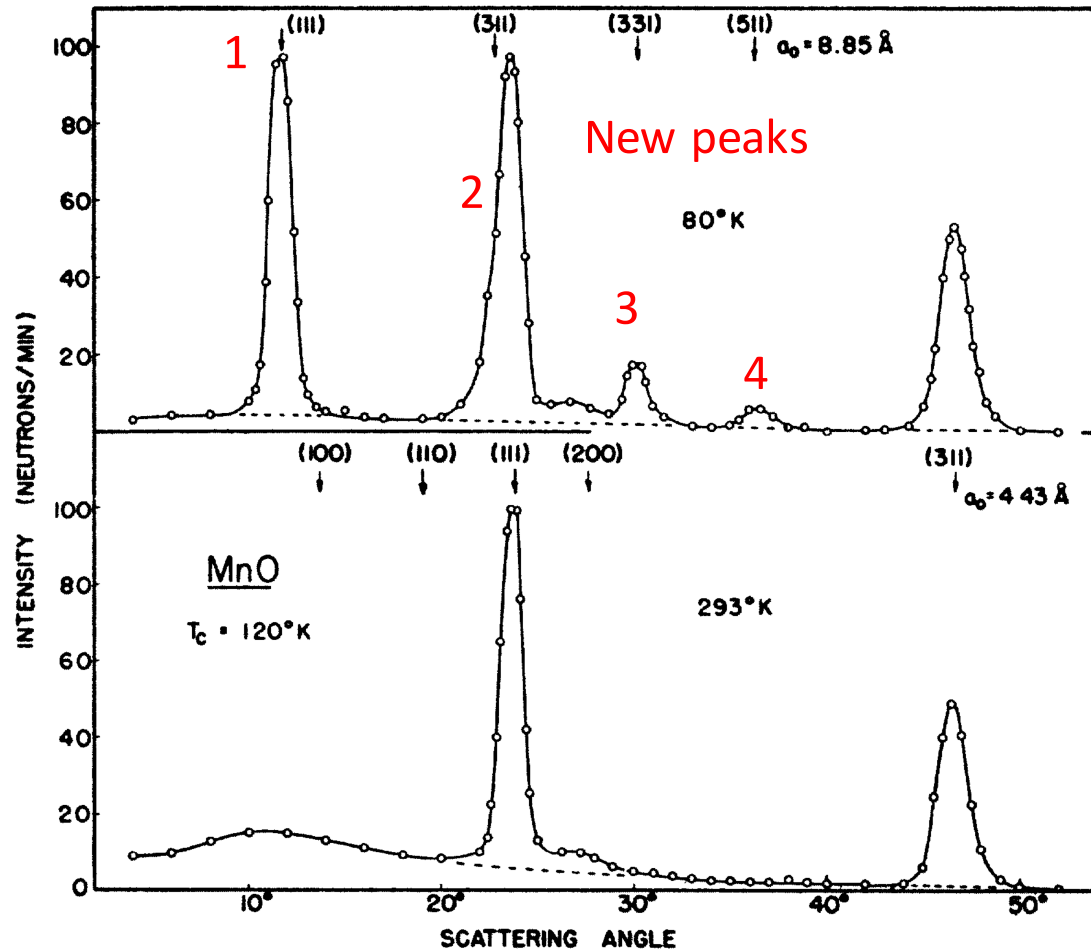




# Phase diagram



# Scattering theory: Structure Factor



Magnetic phase transition

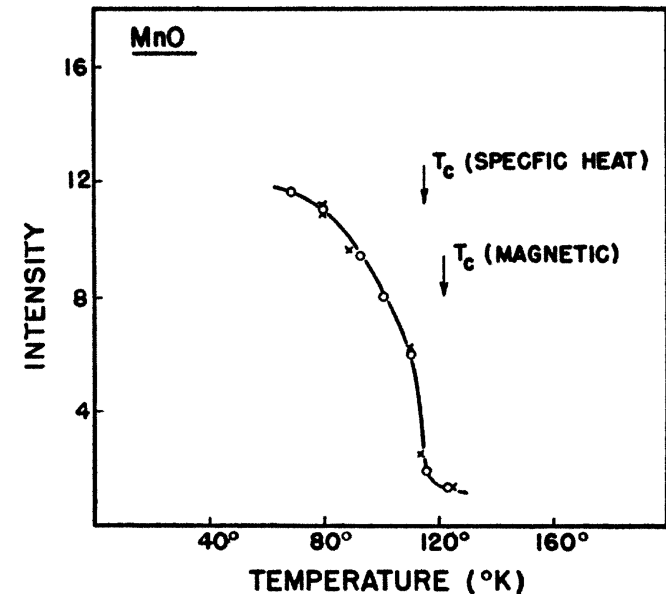
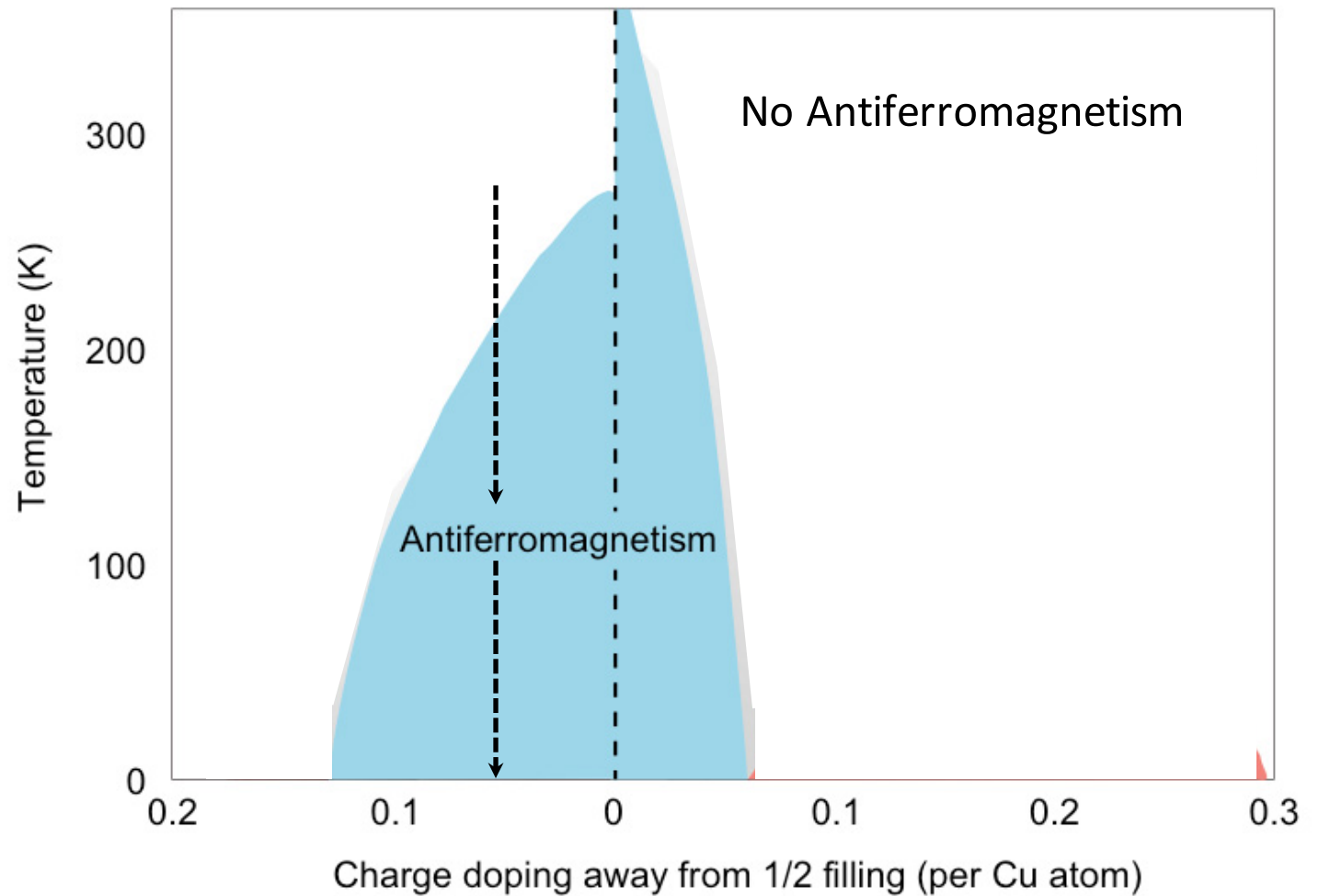
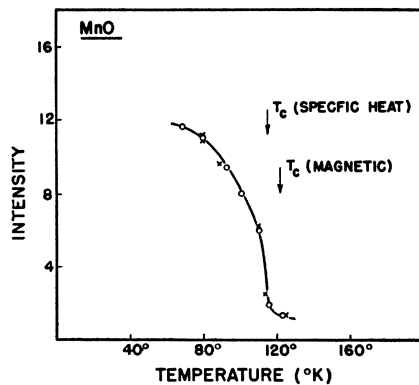
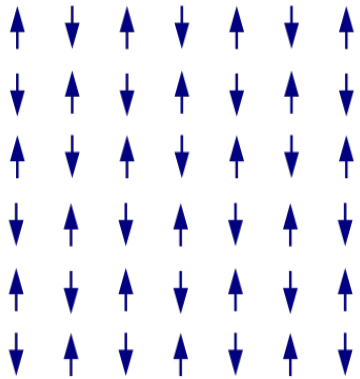


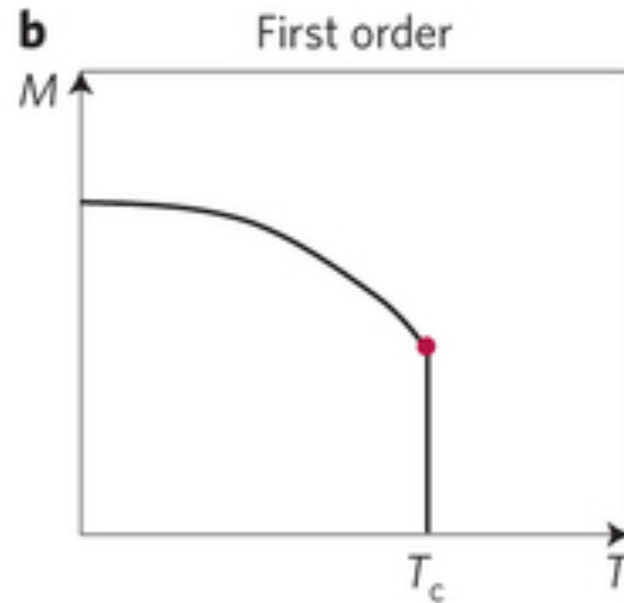
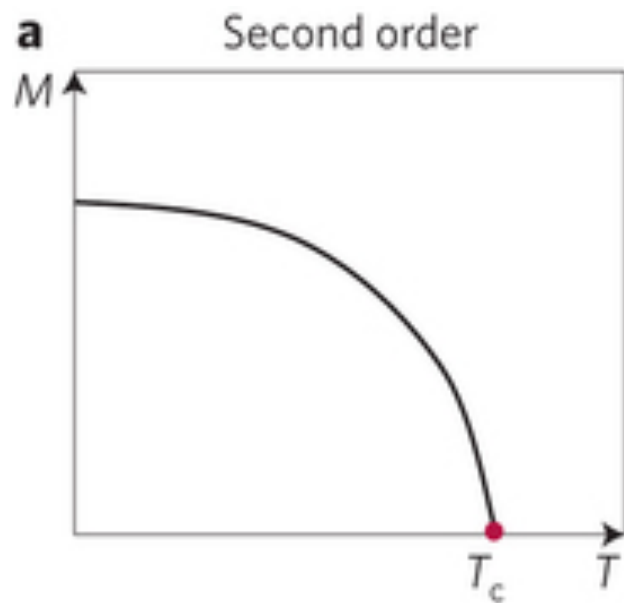
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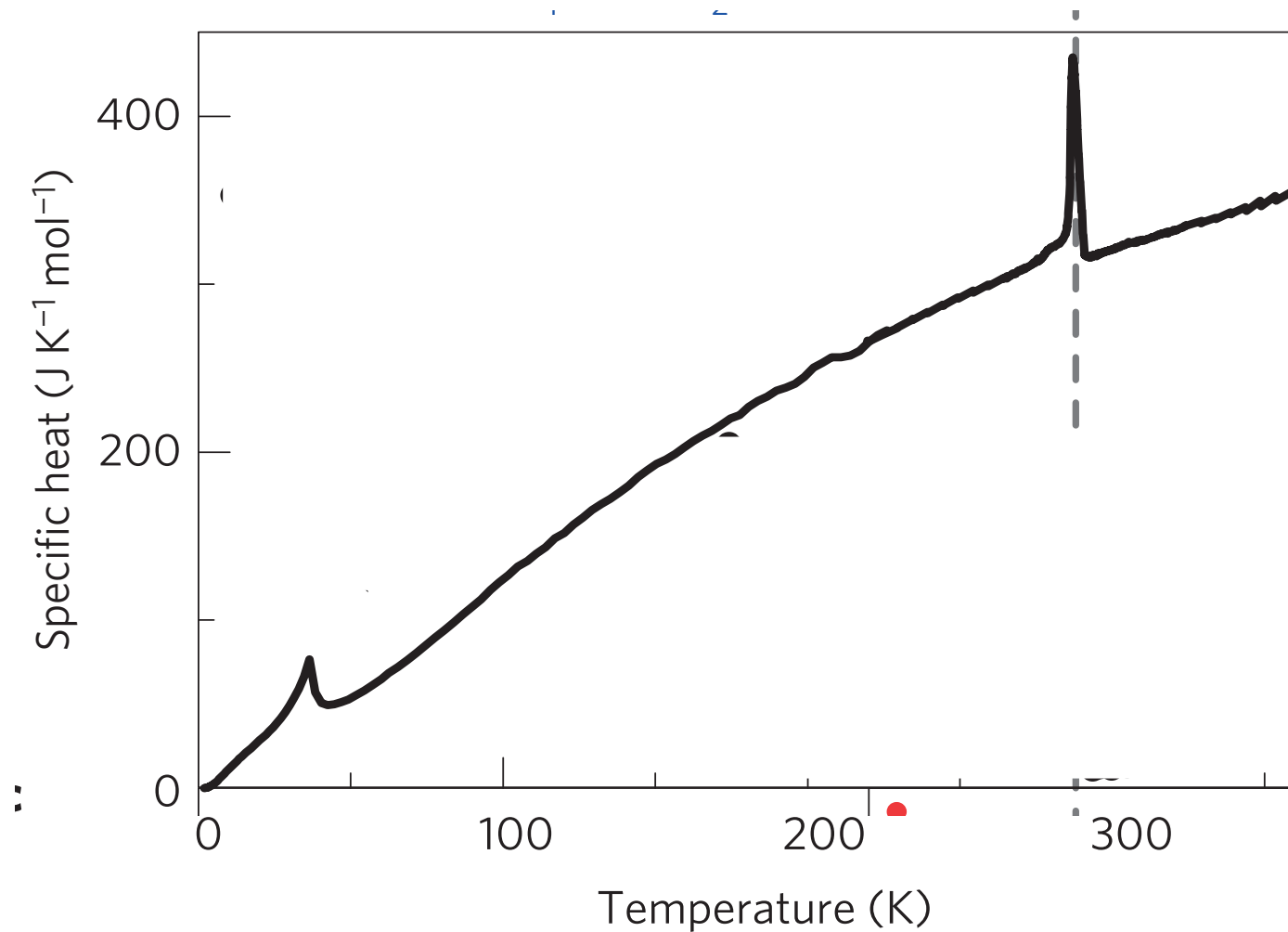
# Magnetic order



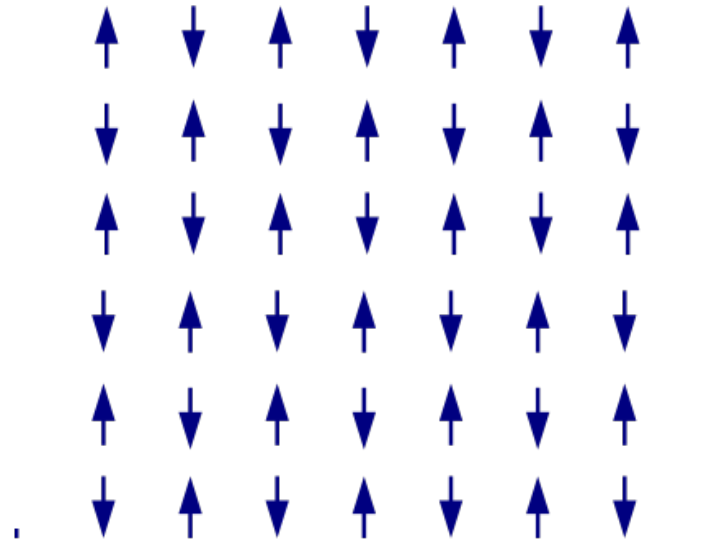
# Order Parameter M



# Heat Capacity and phase transitions



# Symmetry breaking



ANTI-FERROMAGNETISM BREAKS TRANSLATIONAL SYMMETRY OF THE CRYSTAL STRUCTURE.

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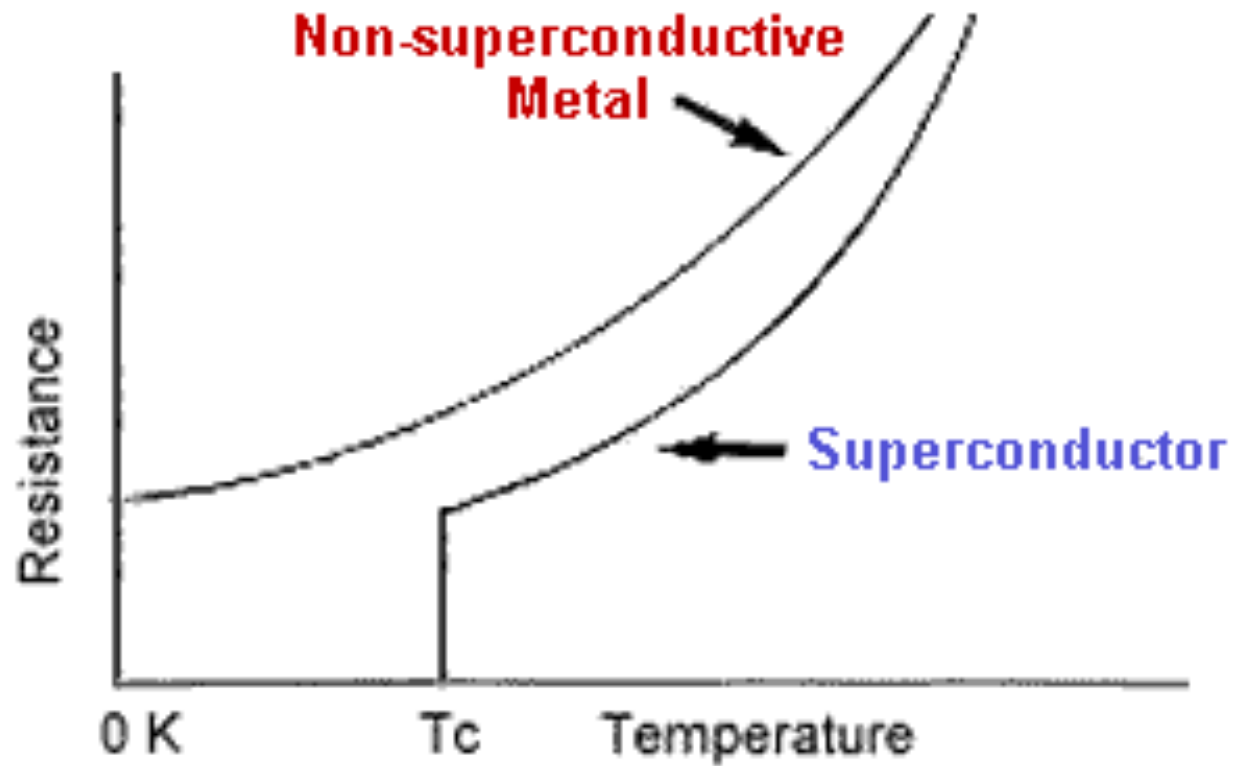
Landau theory

## Superconductivity

Intro & applications

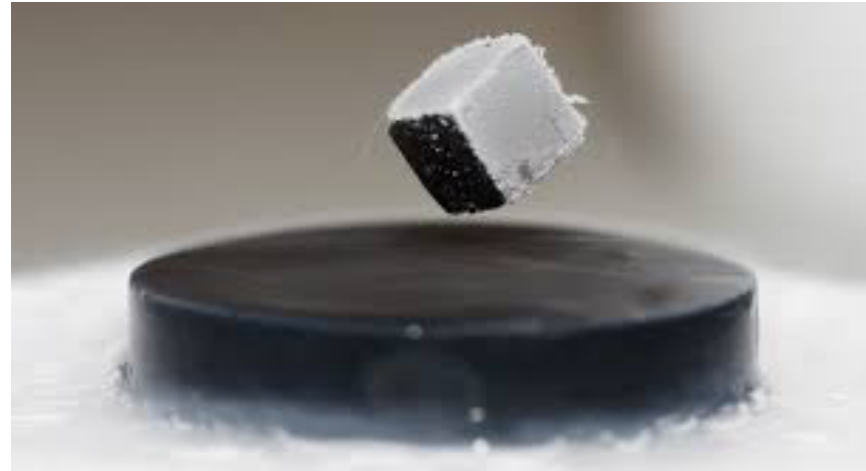
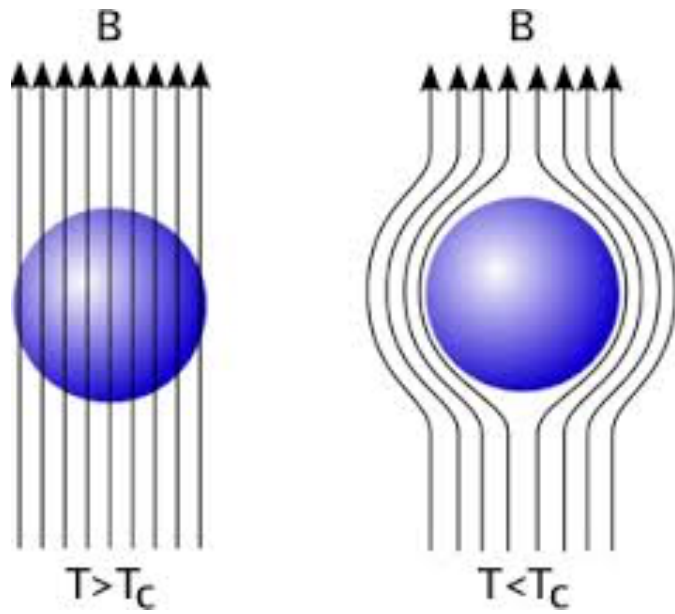
Specific heat

# Superconductivity

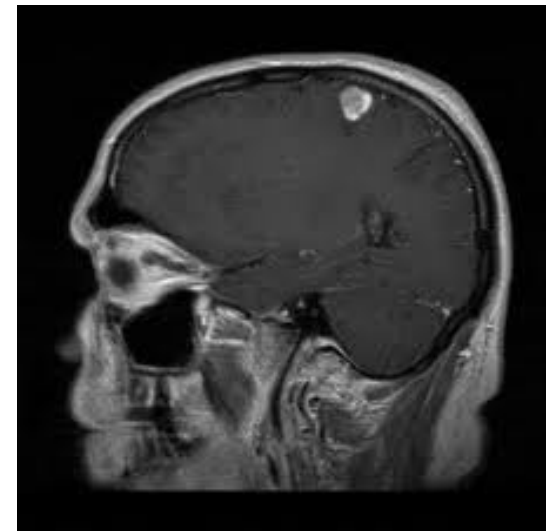
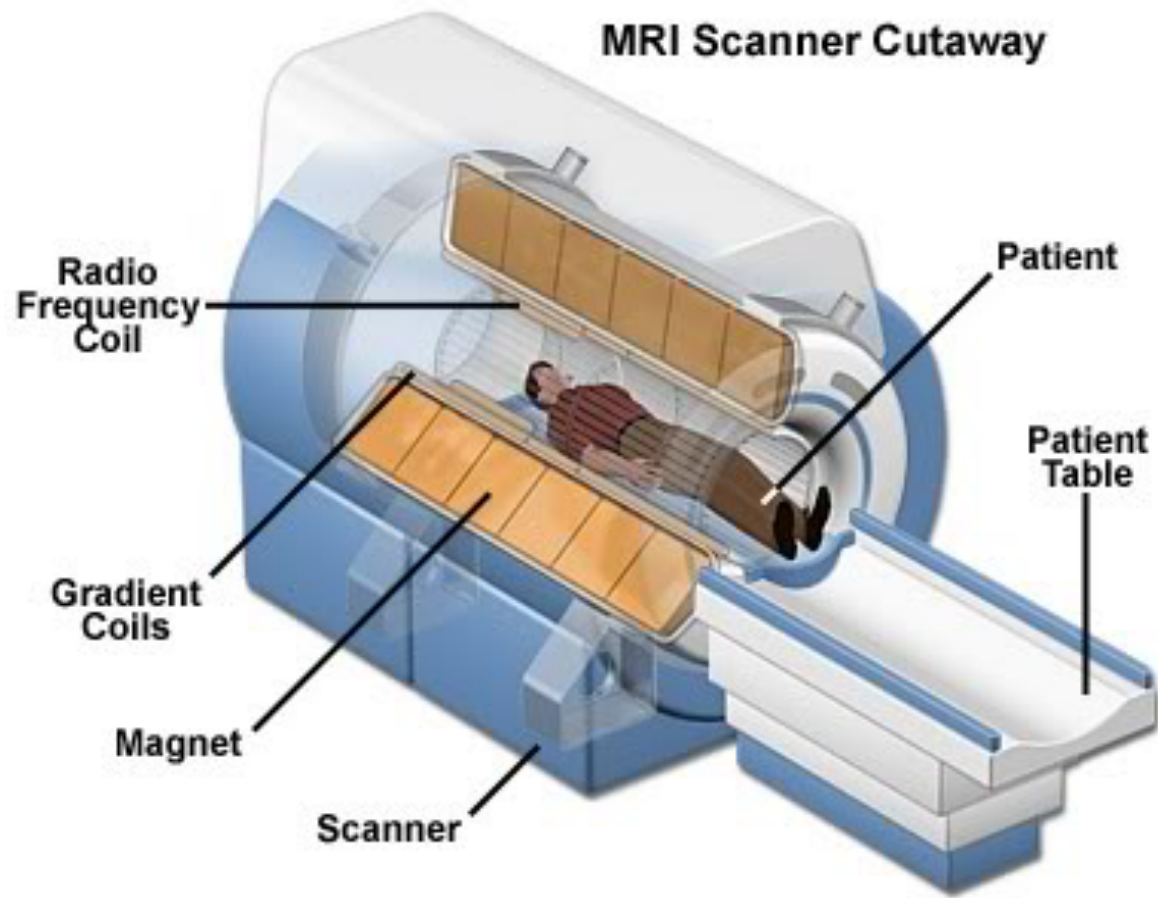




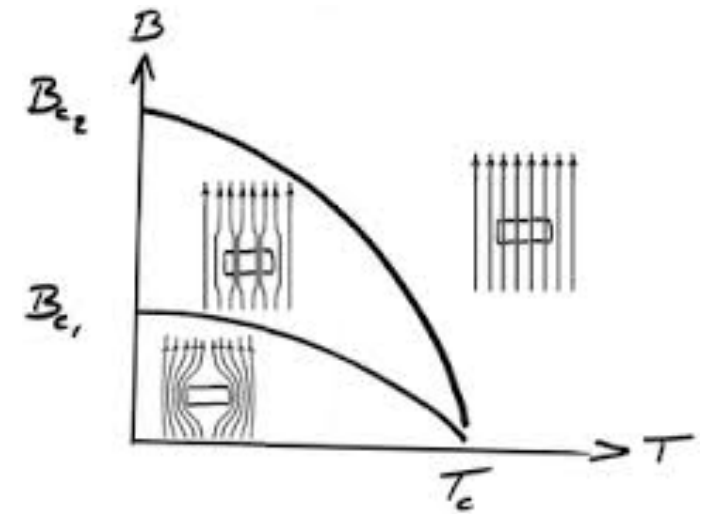
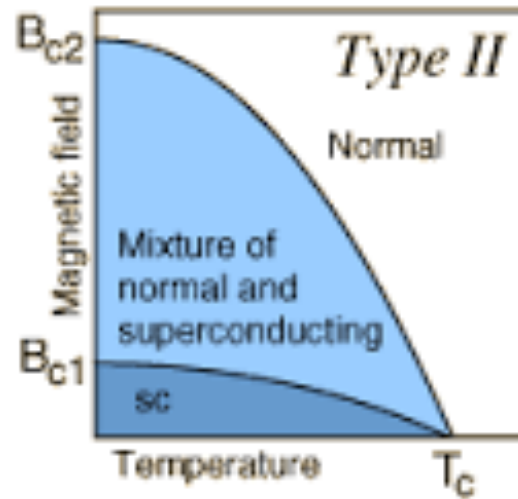
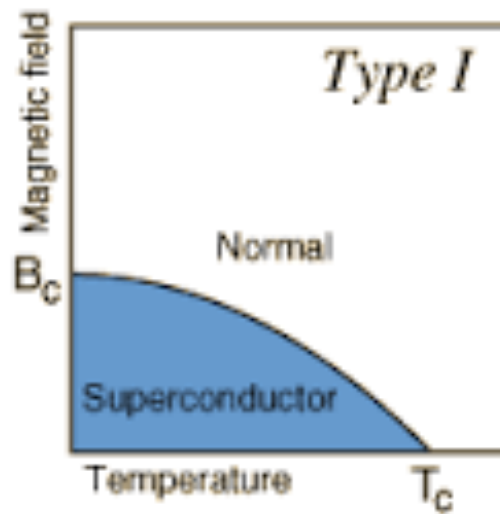
# Meisner effect



### MRI Scanner Cutaway



# Two types of Superconductors



# BCS-Theory of Superconductivity

Bardeen–Cooper–Schrieffer **theory**

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

**Low-Temperature Superconductivity**  
December was the 50th anniversary of the theory of superconductivity, the flow of electricity without resistance that can occur in some metals and ceramics.

**ELECTRICAL RESISTANCE**  
Electrons carrying an electrical current through a metal wire typically encounter resistance, which is caused by collisions and scattering as the particles move through the vibrating lattice of metal atoms.

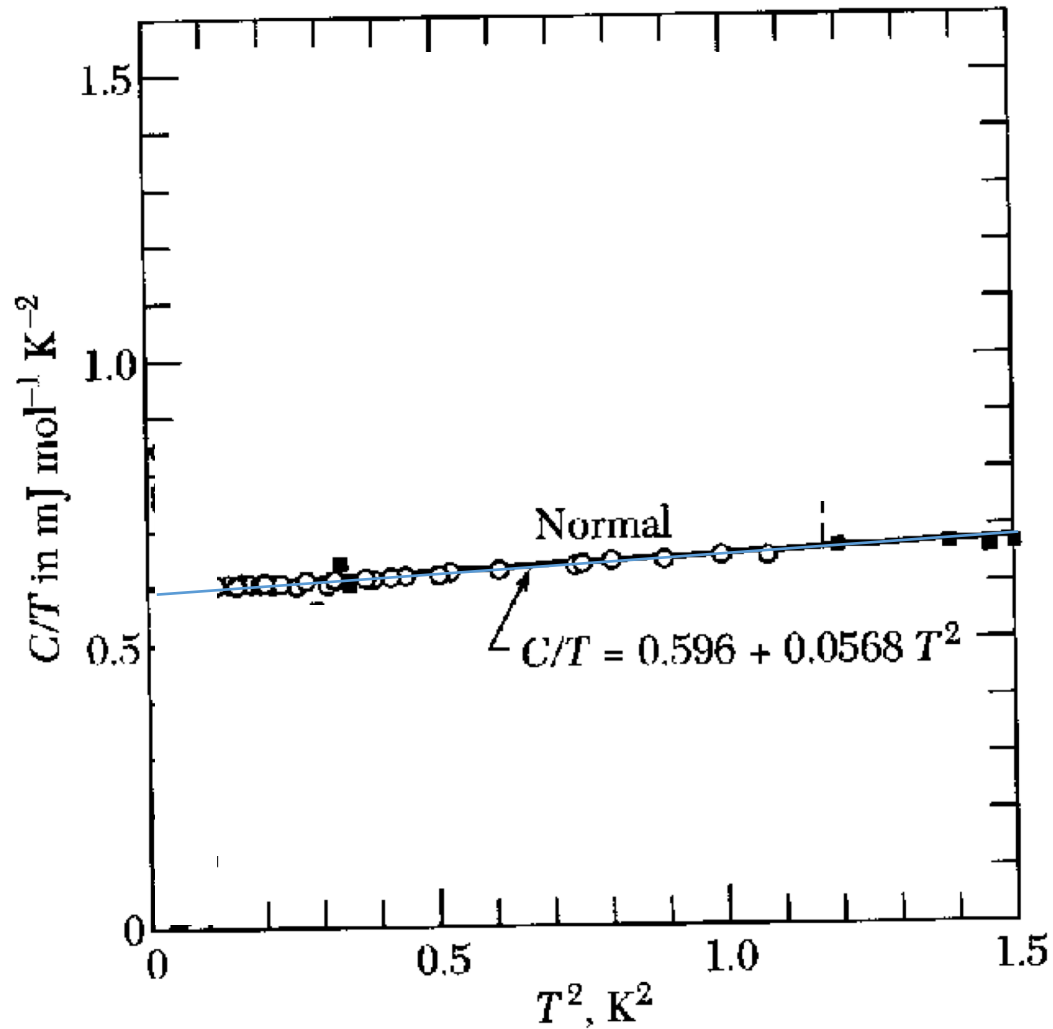
**CRITICAL TEMPERATURE**  
As the metal is cooled to low temperatures, the lattice vibration slows. A moving electron attracts nearby metal atoms, which create a positively charged wake behind the electron. This wake can attract another nearby electron.

**COOPER PAIRS**  
The two electrons form a weak bond, called a Cooper pair, which encounters less resistance than two electrons moving separately. When more Cooper pairs form, they behave in the same way.

**SUPERCONDUCTIVITY**  
If a pair is scattered by an impurity, it will quickly get back in step with other pairs. This allows the electrons to flow undisturbed through the lattice of metal atoms. With no resistance, the current may persist for years.

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

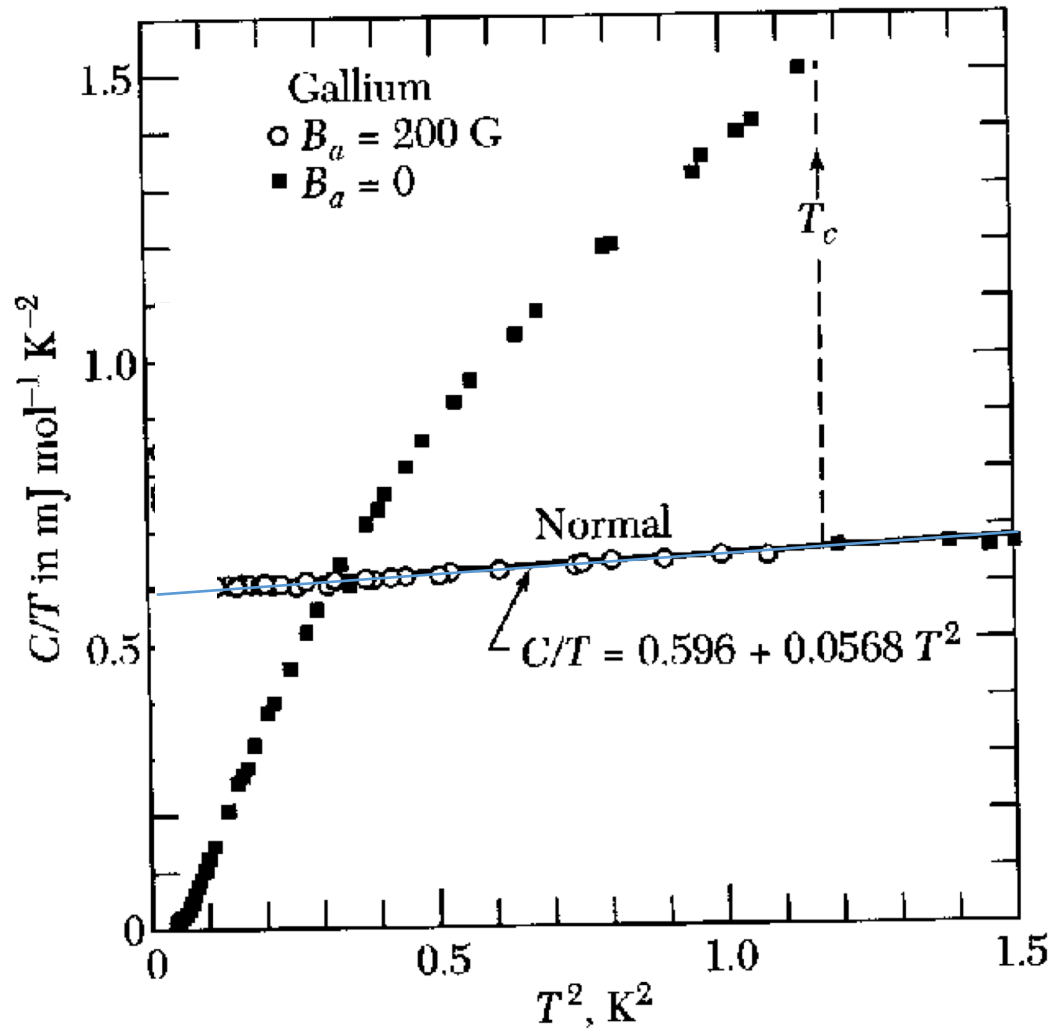
# Heat capacity



(a)

Gallium @ Magnetic field 200 Gauss

# Heat capacity



(a)

Gallium @ Magnetic field 200 Gauss

# Density of states

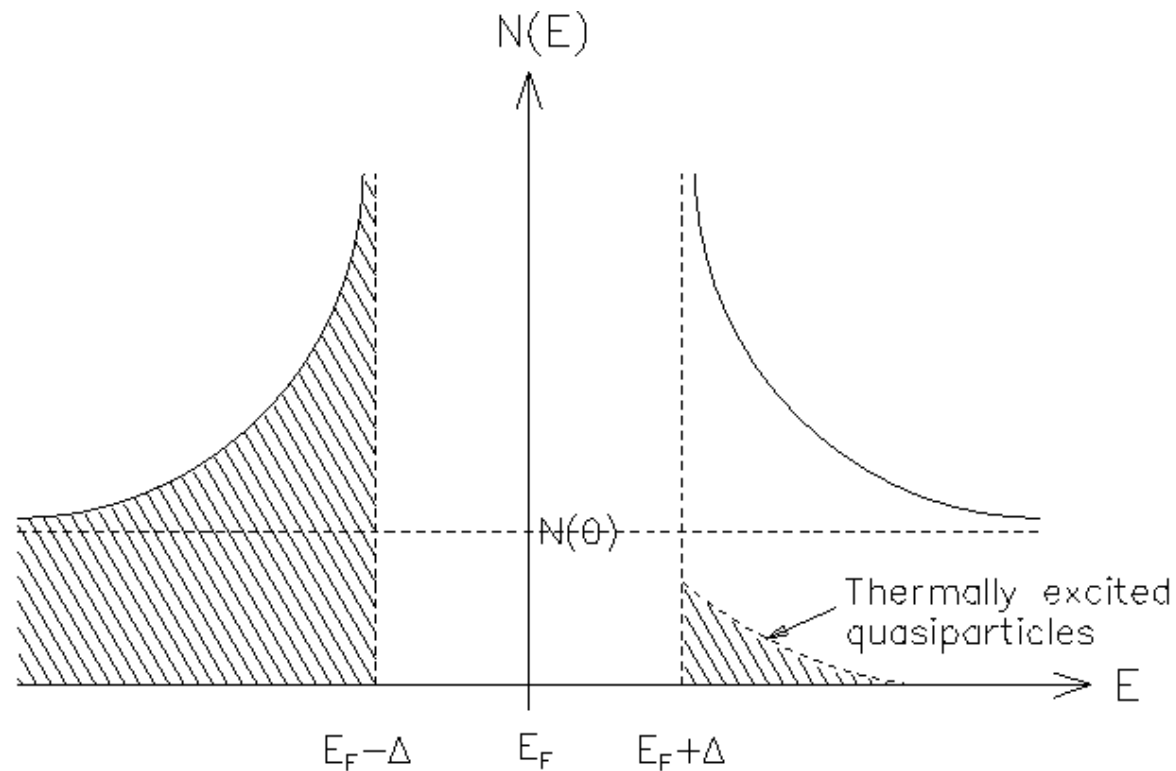
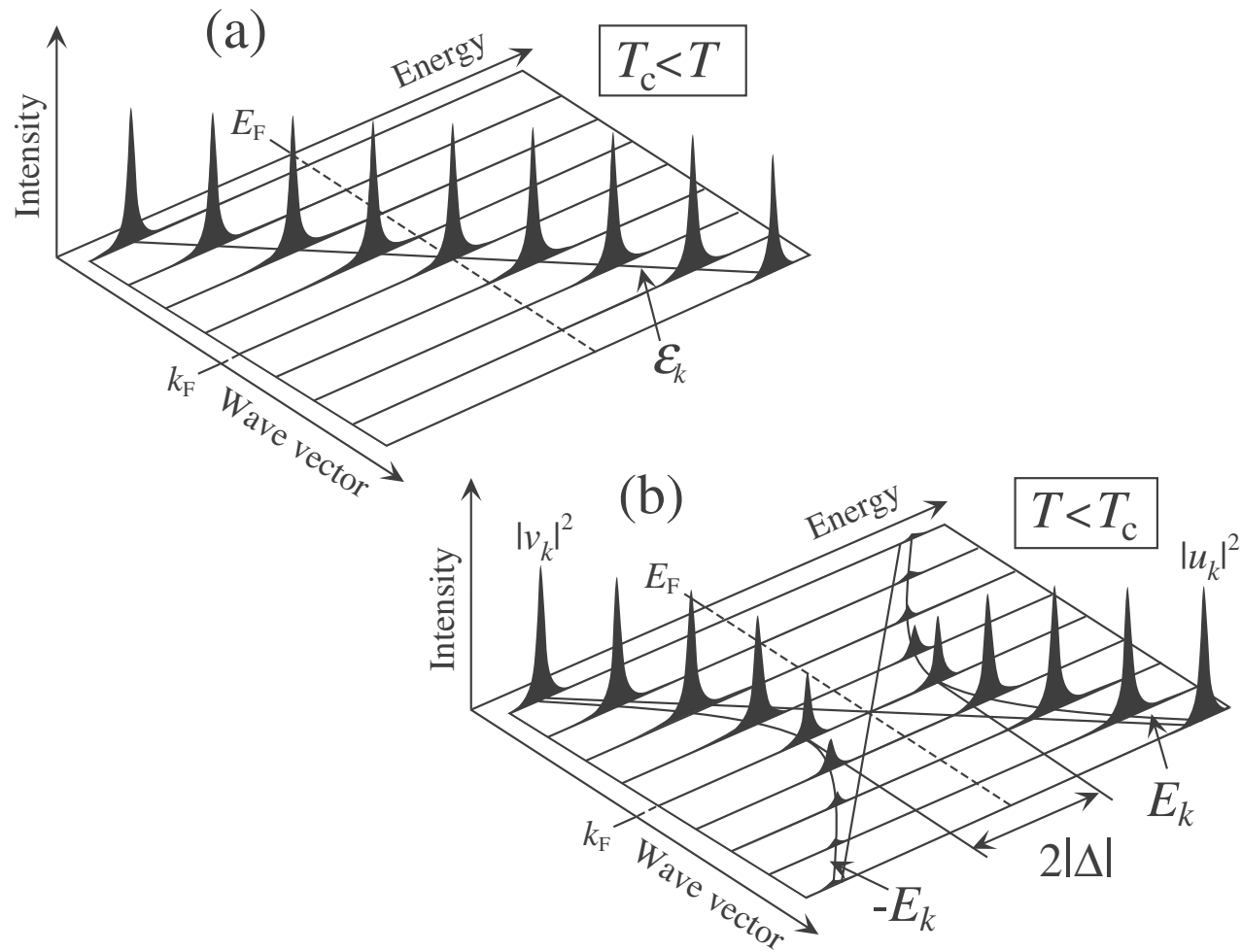


Figure 2.7: The density of states for a BCS superconductor at  $T > 0$  K. As  $T$  is increased above absolute zero, Cooper pairs are broken and the resulting normal electrons occupy states above  $E_F + \Delta$ .

# Superconducting gap



Does a superconductor have a Fermi surface?



# BCS-Theory predictions

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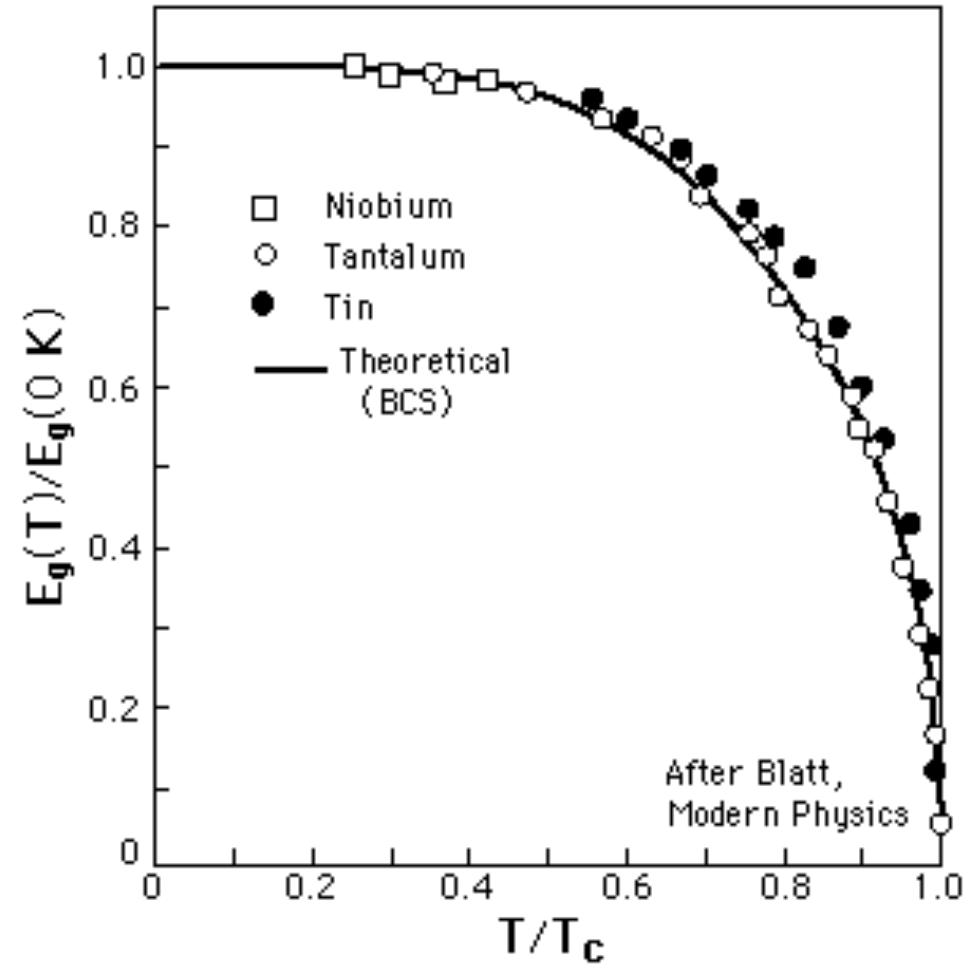
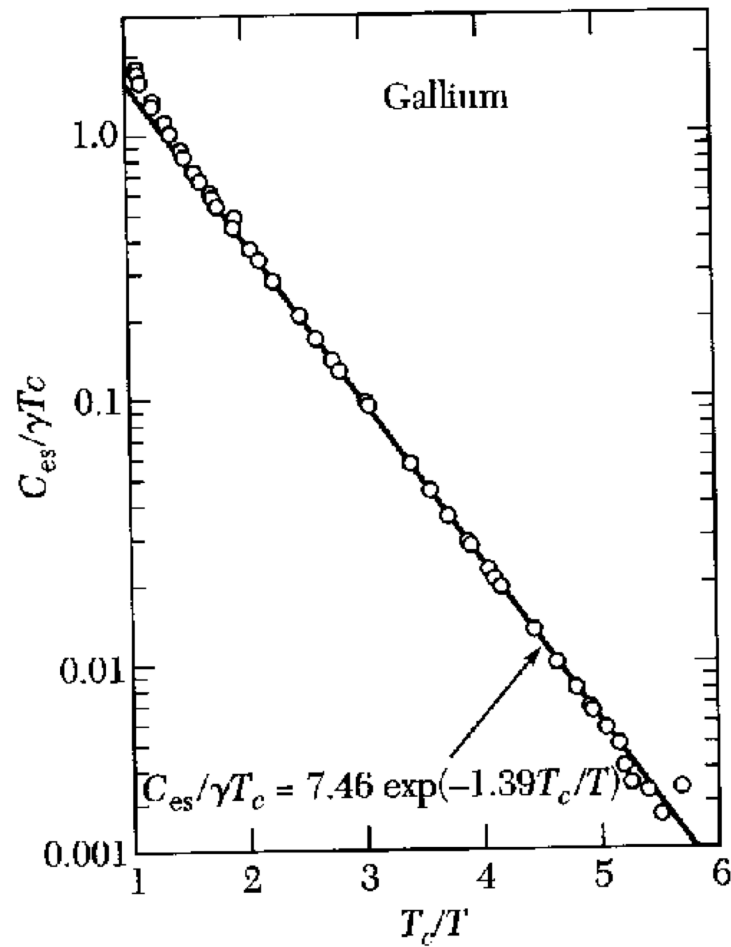
(1) A superconducting gap was predicted.

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

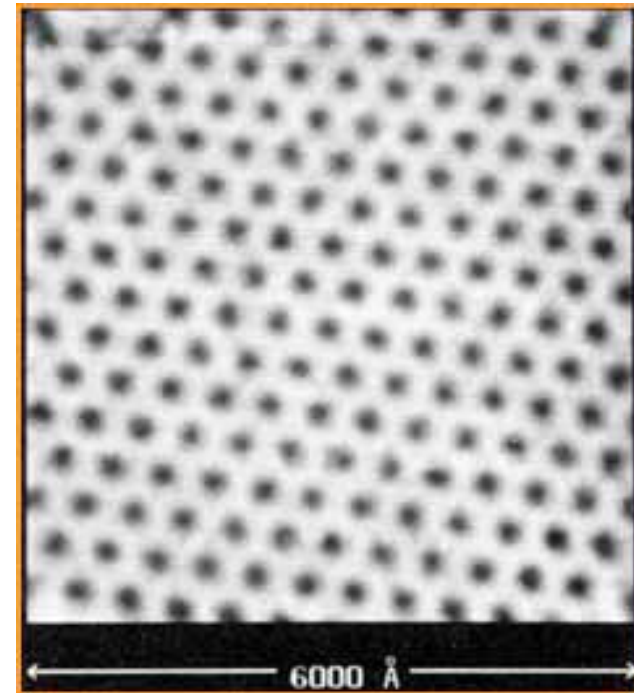
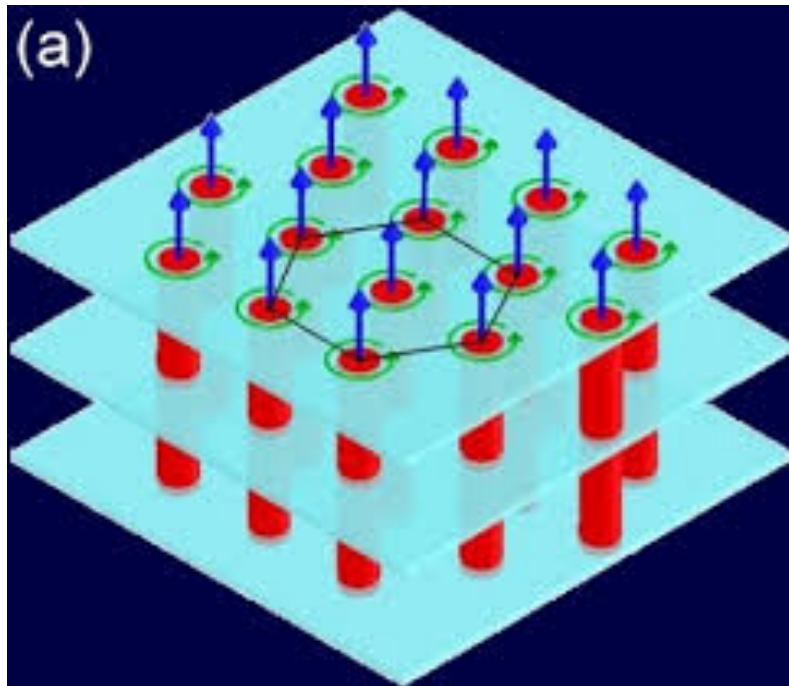
$$(3) \text{Heat capacity: } C \sim e^{\frac{-\Delta}{k_B T}}$$

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

# Predictions vs Experiment



# Vortex lattice



Superconducting coherence length (= core size):

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