Solid State Physics

The “biggest” part of physics in terms of the number of active researchers

Fundamental science behind materials we use in technology

A lot of cool effects that we understand: e.g. topological insulators, multiferroics, superconductivity

and don’t understand: e.g. high temperature superconductivity,
Some effects predicted, but not yet discovered

(e.g. quantum spin liquids)

Materials by design:
Given a property try to theoretically predict which material would have this property?

Say I want a material that is a transparent conductor. Can we predict which material would have this property out of all chemically stable materials?
My research

I study solids by scattering experiments

Scattered particle → sample
Incident particle

To learn more come to my colloquium on Wednesday
Basic properties of solids – That we (often) understand and utilize

**Electrical**
- Why are some conductors and some insulators?
- What are semiconductors? How related to devices? (diodes, transistors, etc.)
- Superconductors
- How solids respond to EM fields?

**Magnetic**
- Why are some ferro-, antiferrro, ferri-, antiferri-, para- or diamagnetic?
- How understand phase transitions?
- Coupling to electrical properties (giant and colossal magnetoresistance)

**Thermal**
- Why are metals better conductors of heat than insulators?
- Specific heat and thermal conductivity
- Thermal expansion

**Mechanical and Structural**
- What holds solids together?
- Crystal structures
- Elastic properties (how respond to stress)
Basic properties of solids – That we understand and utilize continued

Electrical
Magnetic
Thermal
Mechanical and Structural

Optical properties
- Why do metals reflect well? Why are some solids transparent? Colored?
- Optical spectra
What makes solid different from a liquid?

a) Self bounded
b) Rigid
c) Ordered

More than one answer may or may not be right
What is the difference between a liquid and a gas?

a) Self bounded
b) Gas never ordered, liquid may be

c) Sometimes it’s hard to tell

Phase Diagram

Critical point
Phase transitions – many examples in solids

Net magnetic moment
Or magnetic susceptibility

Ferromagnetic

Paramagnetic

$T_c$ (c=Curie or Critical)

Electrical resistivity

SC

Normal

T
How does one approach the physics of solids?

The Fundamental Problem

- Huge number of particles (Roughly $10^{23}$/cm$^3$ in a solid)
- All particles strongly interacting
- Interactions mostly Coulombic

Need quantum mechanical formalism to understand

Where do we start?
1st step: Schrödinger Equation

\[ H\psi = E\psi \]

where

\[ \psi = \psi(\vec{R}_i, \vec{P}_i, \vec{r}_i, \vec{p}_i) \]

Classical Hamiltonian:

\[ H = \sum_i \frac{\vec{P}_i^2}{2M_{Ni}} + \sum_i \frac{\vec{p}_i^2}{2m_{el}} + V(\vec{R}, \vec{r}) \]

all nuclei

all electrons
The fundamental Hamiltonian

\[ H\psi = \frac{-\hbar^2}{2M_N} \sum_i \nabla^2_{R_i} \psi + \frac{-\hbar^2}{2m_e} \sum_i \nabla^2_{r_i} \psi \]

\[-\sum_{i,j} \frac{(Ze)e}{|r_i - R_j|} \]

\[+ \frac{1}{2} \sum_{i,j} \frac{e^2}{|r_i - r_j|} + \frac{1}{2} \sum_{i,j} \frac{(Ze)^2}{|R_i - R_j|} \]

Large number of particles makes it unsolvable

Can solve for an isolated H atom exactly

\( H_2, \) He, etc. some approximation needed; more particles – hopeless?

Ignore spin, Pauli exclusion
The fundamental Hamiltonian

\[ H\psi = \frac{-\hbar^2}{2M_N} \sum_i \nabla^2_{R_i} \psi + \frac{-\hbar^2}{2m_e} \sum_i \nabla^2_{r_i} \psi \]

\[ -\sum_{i,j} \frac{(Ze)e}{|\vec{r}_i - \vec{R}_j|} \]

\[ + \frac{1}{2} \sum_{i,j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|} + \frac{1}{2} \sum_{i,j} \frac{(Ze)^2}{|\vec{R}_i - \vec{R}_j|} \]

Large number of particles makes it unsolvable

Can solve for an isolated H atom exactly

\( H_2, \) He, etc. some approximation needed;
more particles – hopeless? No!!

Look for symmetries, simplifying assumptions
Crystals:

1. Regularity of crystal structure
2. $M_{\text{nuclei}} \gg M_{\text{electron}}$

Example: Approximation for dilute gases:

Interactions $\Rightarrow$ formation of individual atoms (noninteracting)

Allow approximations that often work very well, great insight and predictability

Liquids:

Atomic positions are not periodic – impossible to solve unless some idea from crystals or gases can be applied
Approximations to the Standard Hamiltonian

1. Adiabatic or Born-Oppenheimer approximation: \( M_{\text{nuclei}} \gg M_{\text{electrons}} \)

Electrons react instantaneously to the motion of the atoms

Extreme case: \( M_{\text{nuclei}} \rightarrow \infty \)

\[
H\psi = \frac{-\hbar^2}{2M_N} \sum_i \nabla^2_{R_i} \psi + \frac{-\hbar^2}{2m_e} \sum_i \nabla^2_{r_i} \psi
\]

Then

\[
-\sum_{i,j} \frac{(Ze)e}{|\vec{r}_i - \vec{R}_j|} = 0
\]

(Unless we care about lattice vibrations (phonons))

\[
+ \frac{1}{2} \sum_{i,j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|} + \frac{1}{2} \sum_{i,j} \frac{(Ze)^2}{|\vec{R}_i - \vec{R}_j|}
\]

\text{Const.}
2. Consider valence electrons only

Filled shell tightly bound to nucleus

Outer valence electron
Largest spacial extent

Say Na has 11 protons, 11 electrons

Looks like $Z_{\text{eff}} = 1$ proton, 1 electron
But still many atoms!!!

$$H\psi = \frac{-\hbar^2}{2m_e} \sum_i \nabla^2_{r_i} \psi - \sum_{i,j} \frac{(Ze)e}{|\vec{r}_i - \vec{R}_j|} + \frac{1}{2} \sum_{i,j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|}$$

K.E. valence el. P.E. valence el.

El. –el. interaction most difficult and interesting
What we are going to do in the course

1. Learn about crystal structures and why they are important
2. Diffracton as a tool for studying crystals but also because….
   Electrons constantly in solids diffract!!!
3. How atoms in crystals vibrate
4. Free electron gas as the first approximation of metals
5. Electrons in a weak periodic potential
6. Basics of band theory
7. Introduction to magnetism
8. Electrical transport (electrical conductivity)
9. Thermal transport (thermal conductivity) and the physics of thermoelectrics
Grading

Homework: 50% (Due in class Wed. some after 2 weeks)
Final: 50% (Open book)
Exam time, place: TBA, stay tuned…

Office hours: Mon 11-12:30 in my office Duane F625

1st homework already posted on the website.
Textbook: Ziman, Introduction to Solid State Physics
I will also be using material from other books, e.g. Ashcroft and Mermin, which I will copy and distribute.

Other useful books:

1) Introduction to Solid State Physics (8th Ed.), by Charles Kittel. This has been the most popular undergraduate level solid state text for more than 20 years.

2) Solid State Physics, by Neil Ashcroft and David Mermin. This is the most popular graduate level text. It is wordier than Kittel, more complete, but maybe not much harder.