PHY 555: Solid State Physics I

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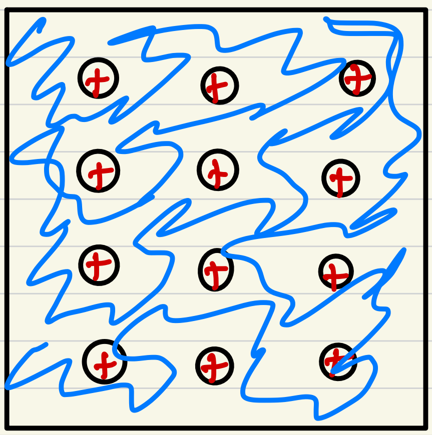
Office Hours: Mon: 10-11am, Wed: 10am-12pm

Book: Solid State Physics by Grosso and Parravicini
(see syllabus for other resources

What is ~~solid state physics~~? Condensed matter physics

- The description of systems containing many atoms bonded together in a condensed phase
- Length scale of CMP ~ Å = 10^{-10} m (~1.89 Bohr)
  - Order of atomic spacings in solids / liquids
  - Full range of physics is 10^{-12} (microscopic) – 10^{-1} m ← macroscopic
- Energy scale of CMP ~ 1eV (~ 1/27.2 Ha)
  - emergent energy scale when we put atoms together
  - Full range: 1 μeV – 1 keV
- Systems that we treat:
  - Atomic nuclei: - Positive point charges (mostly classical)
  - Electrons: - Sometimes neg. charged particles
    - Sometimes continuous waves
    - Sometimes classical sometimes quantum



- How do we rigorously describe such a system?
  - Many-body Schrödinger Equation:

    (for now nonrelativistic)

    $$i\hbar \frac{d}{dt} \Psi(\vec{r}, \vec{R}, t) = \hat{H} \Psi(\vec{r}, \vec{R}, t)$$

    ($\vec{R}$ ← coordinates of all nuclei; $\vec{r}$ ← coordinates of all electrons)

$$\hat{H} = \underbrace{\sum_i \frac{\vec{p}_i^{\,2}}{2m}}_{\text{K.E. of electrons}} + \underbrace{\sum_I \frac{\vec{P}_I^{\,2}}{2M_I}}_{\text{K.E. of nuclei}} - \underbrace{\sum_{I,i} \frac{Z_I e^2}{|\vec{r}_i - \vec{R}_I|}}_{\text{electron-nuclei Coulomb attraction}} + \underbrace{\frac{1}{2}\sum_{i \neq j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|}}_{\text{electron-electron Coulomb repulsion}} + \underbrace{\frac{1}{2}\sum_{I \neq J} \frac{Z_I Z_J e^2}{|\vec{R}_I - \vec{R}_J|}}_{\text{nuclei-nuclei Coulomb repulsion}}$$

- All properties of interest to CMP given by Ψ
- often can make simplifications:
  - * If we are interested in static properties:

    $$\hat{H}\Psi = E\Psi$$

  - * Note that $\frac{1}{m_i} \gg \frac{1}{M_I}$, so we can drop nuclear K.E.
- Many-Body S.E. still impossible to solve in majority of cases!!!
  - * Why? Consider macroscopic limit: 10^{-1} m

    $1\ \text{cm}^3$ of Carbon ~ 2 grams $\sim 1 \times 10^{23}$ atoms

    $\sim 6 \times 10^{23}$ electrons

* The problem: Electron-electron interaction : $\frac{1}{2}\sum_{i \neq j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|}$

Cannot break down the problem: $\Psi(\{\vec{r}_i\}) \neq \Psi(\vec{r}_1)\Psi(\vec{r}_2)\cdots$

- How do we proceed? "Approximate practical methods" - Dirac

* Map many-body system onto single particle in effective potential
* Map real material on to simple model
* Find a small parameter and do perturbation theory
* Treat degrees of freedom classically / semi-classically
* ...

<u>Why</u> study solid state physics?

- <u>Impact</u> → things are made out of solids!
  * Consider a computer:
    - screen: glass
    - keyboard: plastic
    - transistors: semiconductors
    - interconnects: metals
    - storage: magnets

  - Why are these different?
  - Which material do we choose?
  - How can we engineer them?

- <u>Interest</u> → Fascinating fundamental physics
  * Emergence: "More is different" Phil Anderson
    • such a variety of phenomena from <u>many</u> electrons and nuclei interacting via Coulomb interactions

- Superconductivity: Macroscopic coherent quantum state of many electrons conducting without resistance
- Exotic "particles": Emerging out of many electron systems:
  - Dirac, Weyl, Majorana fermions
  - (quasi) particles w/ fractional charge
  - Magnetic monopoles (kind of ◡̈)

What will we cover in this class?

- I. Basic properties of solids, strategies for describing them
- II. Electronic structure
- III. Including the lattice: phonons, etc.
- IV. Excitations: Scattering, optical, transport properties
- V. Magnetic properties
- VI. Superconductivity (???)