Notes on Introduction to Condensed Matter Physics

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1 Basic Introduction

1. Condensed Matter: $\sim 10^{23}\ /cm^3$
2. Major Study: Electrons, Phonons, The interactions between
3. Drives: New materials & New technologies

2 Conventional Metal Physics: Electrons and Phonons

1. Basic Properties of Normal Metals: • Ductile • Excellent electrical conductor • Excellent thermal conductor • Most are weak paramagnet, some ferromagnet • Opaque
   • At low T: ρ increases with T $\quad \chi \sim Const. \quad c_V \propto T$
2. Drude Free Electron Model:
   • Assumptions: • Free electrons (Ignore interaction with lattice) • Independent electrons (Ignore interactions between electrons • Electrons were treated as independent classical particles

• Maxwell-Boltzmann distribution

• Successes: • Electrical conductivity and thermal conductivity • Wiedemann-Franz law (by luck!) • The Hall effect and magnetoresistance • AC conductivity and optical properties of metals

• Problems: • Heat capacity puzzle: $c_V = \frac{3}{2} n k_B = Const.$ • The susceptibility puzzle: χ does not change with temperature, non-Curie like $\chi \sim 1/T$

3. The Sommerfeld Model: • Free Electron Gas + Schrodinger Equation + Fermi Statistics

   • The Fermi Surface: In 3D $E_F \sim n^{2/3}$ • Typical Values: $E_F \sim 7\ eV$, $k_F \sim 1 \times 10^8\ cm^{-1}$, $T_F \sim 8 \times 10^4\ K$, $v_F \sim 2 \times 10^8\ cm/s$ • DOS In 3D: $D(\varepsilon) \sim \varepsilon^{1/2}$ • Linear T Heat Capacity at Low T

   • Pauli Paramagnetism (at low T): $\chi = \mu_B^2 D(E_F) = const.$

   • Successes: • Realized the importance of Fermi distribution • Established the k-space language for electrons • Introduced Fermiology • Resolved the Pauli susceptability puzzle • Resolved the heat capacity puzzle • Resolved the thermopower puzzle • Explained the Wiedemann-Franz Law

4. Landau's Fermi Liquid Theory: •Quasi-particle: Same charge, spin, momentum as non-interacting electron • Adiabatic Continuity, Only valid at low T and low energy • Qualitatively explain the susceptibility, heat capacity Only require a Fermi sea • Entropy, distribution function unchanged • Energy modified by the effective mass & the Fermi interaction function • Low energy excitation like single particle • $\varepsilon = \frac{\hbar^2 k^2}{2m^*}$ • $c_V = \frac{1}{3} \frac{m^* k_F}{\hbar^2} k_B^2 T$ • $\chi = \frac{m^* k_F}{\hbar^2 \pi^2} \frac{1}{1+F_0^a} \mu_B^2$ • Landau parameter: m^*, F_0^a • Wilson ration: $R_W = \frac{\pi^2 k_B^2}{3\mu_B^2} \frac{\chi}{\gamma}$ • For non-interacting electron gas $R_W = 1$ • T^2 Law (Experimental Signature): qp-qp scattering • Scattering rate $\frac{1}{\tau} \sim k_B T \cdot k_B T \propto T^2$ • But electron seems to be a wrong place to start for many novel phenomena • Spinon, holon, fractional charge: Collective mode looks like a fraction of an electron

5. Bloch Theory: • Bloch Theorem: For periodic potential, $\psi_{nk}(\boldsymbol{r}) = \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} u_{nk}(\boldsymbol{r})$, where $u_{nk}(\boldsymbol{r}) = u_{nk}(\boldsymbol{R}+\boldsymbol{r})$ • Momentum is no longer a good quantum number • Band index n

   • NFE model: Perturbation to the free electron plane wave states (maximum mixing) (highly delocalized) • First order: $\varepsilon_k^1 = \overline{V}$ • Second order (non-degenerate): $\varepsilon_k^2 = \sum_{g \neq 0} \frac{|V_g|^2}{\varepsilon_K^0 - \varepsilon_{k-g}^0}$ • Second order (degenerate): $\varepsilon_k^2 = \pm |V_n|$ • Energy gap: Level repulsion, Explains metal or insulator

   • +2 Metals: Band overlap

   • Tight Binding Model: (nearly localized) such as transition metal and rare earth metal with partially filled d and f orbitals. • $\psi_k(\boldsymbol{r}) = \sum_{\boldsymbol{R}} \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{R}} \psi_a(\boldsymbol{r} - \boldsymbol{R})$ • Overlap integral: $t_{\boldsymbol{R}} = \int \psi_a^*(\boldsymbol{r} + \boldsymbol{R})(\Delta V)\psi_a(\boldsymbol{r})\mathrm{d}\boldsymbol{r} \rightarrow$ Nearest neighbor approximation • Band width: $W \sim 2zt$, where z is coordination number, t is overlap integral • Useful starting point

6. Lattice Vibrations: • Harmonic Approximation: $V(a + \delta x) = V_0 + \frac{1}{2}\beta(\delta x)^2$ • $\varepsilon = \sum_k (n_k + \frac{1}{2})\hbar\omega$ • Phonons: The quantum of the lattice vibration, $n_k = \frac{1}{\mathrm{e}^{\hbar\omega/kT} - 1}$ • Mono-atomic 1D Chain: $\omega = 2\sqrt{\frac{\beta}{m}} \left|\sin\left(\frac{aq}{2}\right)\right|$

• Di-atomic 1D Chain: Acoustic & Optical phonon • Phonon specific heat: Debye model: • Assume linear dispersion • Define a cutoff in the integral: Debye frequency

• $T \to 0$ $c_V \sim T^3$ ⇐Blackbody radiation

7. Specific Heat: • Directly related to internal energy • To extract important microscopic parameters • To study phase transition • Calorimetry: What, How, Better resolution and accuracy, Flecibility • Adiabatic Nernst Calorimeter: Slow, Heat leak problem, Need big sample

   • Relaxation time calorimeter: $\Delta T = \Delta T_0 e^{-t/\tau}$, where $\tau = c_V l/\kappa S$ (with addenda)

   Advantage: Accurate, Fast, Microgram crystals, Small, Work in extreme conditions

   Disadvantage: The addenda

   • Membrane calorimeter: Nano-gram crystals, Measure in-situ evaporated thin films, Extreme conditions

   • Heater: Resistance stable with T • Thermometer: Resistance has Linear relationship with T

8. Anharmonic Potential: • Universal ⇐ $V = 0$ when $r \to \infty$ • Phonon-phonon interaction: No longer independent excitations ⇒ Phonon heat conduction (low$T$, high$T$) • Thermal Expansion: • $\alpha = \frac{1}{l}\frac{\partial^2 l}{\partial T \partial p} = \frac{1}{3V}\frac{\partial^2 V}{\partial T \partial p}$ • Provide similar information as specific heat • Bad in engineering

   • XRD → Measure l or V, High resolution, Hard to use in extreme physical conditions

   • Capacitive dilatometer: High resolution (capacitance bridge) (0.01 Å), ultra low T and large B (compact design)

   • Negative thermal expansion: ZrW_2O_8 → Rigid Unit Modes

9. Main Frame: Landau Fermi Liquid Theory + Band Theory

3 Transport

1. Basic Notions: • Movement of Particles or Quantities • Non-equilibrium steady state • $\boldsymbol{J} = L \cdot \boldsymbol{F}$

   • Very informative and instructive, esp. on Novel materials and in Extreme conditions

   • Normally the first to be carried out • Close relations to device applications

2. Fractional Quantum Hall Effect: • Ultra low T, Super strong B, Very clean • Strong electron correlations

   • Most precise method to measure h

3. Cryogenic Technology: • Dilution fridge method: He-3 rich & He-3 poor phase at $T < 0.87\ K$

   • He-3 diffuse, absorb heat • Down to ~ 10 mK

   • Superconducting magnet: up to 20 tesla ⇐ critical field

   • Super high megnetic field: Florida-Bitter resistive magnet, Hybrid magnet

4. The Boltzmann Transport Equation: • $\frac{\partial f_k}{\partial t}\Big|_{\text{diffusion}} + \frac{\partial f_k}{\partial t}\Big|_{\text{field}} + \frac{\partial f_k}{\partial t}\Big|_{\text{scattering}} = 0$ • $\frac{\partial f_k}{\partial t}\Big|_{\text{diffusion}} = -\dot{\boldsymbol{r}} \cdot \nabla_{\boldsymbol{r}} f_k$ • $\frac{\partial f_k}{\partial t}\Big|_{\text{field}} = -\dot{\boldsymbol{k}} \cdot \nabla_{\boldsymbol{k}} f_k$ • $\frac{\partial f_k}{\partial t}\Big|_{\text{scattering}} = -\frac{f_k - f_k^0}{\tau}$

5. Electrical Transport: •$\boldsymbol{J}_e = \sigma \boldsymbol{E}$ • Measurements: Four-probe, Low frequency ac lock-in method
   - Drude model: $\sigma = \frac{ne^2\tau}{m}$ • Semi classical: $\delta \boldsymbol{k} = \frac{e\tau \boldsymbol{E}}{\hbar}$ • Only the surface of the FS changed !
   - Ignore the diffusion effect, Complexity of the FS
   - The Boltzmann transport equation: $\overleftrightarrow{\sigma} = \frac{1}{4\pi^3}\frac{e^2\tau}{\hbar}\int \frac{\boldsymbol{v}_k \boldsymbol{v}_k \mathrm{d}S_F}{v_k}$
   - Cubic symmetry: $\sigma_{x,y,z} = \frac{e^2}{3} v_F l D(\varepsilon_F)$
   - Matthiessen's rule: Different scattering mechanisms don't interfere each other $\Rightarrow$ $\frac{1}{\tau} = \frac{1}{\tau_{imp}} + \frac{1}{\tau_{ph}} + \cdots$
   - Electron-electron scattering: $\frac{1}{\tau} \sim T^2$
   - Electron-lattice scattering: $\rho \sim T$, at high T $\rho \sim T^5$, at low T
   - Electron-impurity scattering: • Roughly, Temperature-independent • Residual resistivity: $\rho(T = 0)$ • Residual resistivity ratio (RRR): $\frac{\rho_{300K}}{\rho_0}$ Higher the better

6. Thermal Transport: •$\boldsymbol{J}_Q = \kappa(-\nabla T)$ • Measurement: One-heater, Two-thermometer
   - Drude: $J_{Qe,x} = \frac{1}{2} n v_x [\varepsilon(T_{x-v\tau} - T_{x+v\tau})] = \frac{1}{3} c_V v l$ • $\boldsymbol{J}_Q = 2\int f_k(\varepsilon_k - \mu)\boldsymbol{v}_k \mathrm{d}\boldsymbol{k}$ • $\kappa_e = \frac{\pi^2}{3}\frac{k_B^2}{e^2} T \sigma$
   - Phonon Thermal Conductivity: Good metals ~ 1%

7. Thermoelectric Power: • Seebeck Coefficient: $S = \frac{E}{\nabla T} = \frac{c_V}{3ne}$ • The piece of heat carried by each charge e
   - Inversely proportional to ε_F • $S = \frac{\pi^2}{3}\frac{k_B}{e} k_B T \left(\frac{\partial \ln \sigma(\varepsilon)}{\partial \varepsilon}\right)\Big|_{\varepsilon=\mu}$ • Reveal abrupt change of electronic stucture
   - Study novel electronic phases and phase transitions, But poorly understood
   - Thermal couple: $V = (S_B - S_A)(T_x - T_0)$ • Thermoelectric power generation: Π-junction consisting of N type & P type material • $V = (|S_N| + |S_P|)(T_h - T_c)$ • No moving part, reliable • Environmental friendly • Arbitrary Shape & Size • Radioisotope thermoelectric generator: For unmanned situations, Low power, Long durations • Thermoelectric refrigeration: Π-junction consisting of N type & P type material • $J_Q = J_e(|\Pi_N| + |\Pi_P|)$

8. Peltier Effect: •$\boldsymbol{J}_Q = \Pi \boldsymbol{J}_e$

9. Onsager reciprocal relations: • $\begin{pmatrix} \boldsymbol{J}_e \\ \boldsymbol{J}_Q \end{pmatrix} = \begin{pmatrix} \sigma & \sigma S T \\ \sigma \Pi & -\kappa T \end{pmatrix} \begin{pmatrix} \boldsymbol{E} \\ \frac{\nabla_{\boldsymbol{r}} T}{T} \end{pmatrix}$ • $\Pi = ST$

10. The Thermoelectric Figure of Merit: •$ZT = \frac{\sigma S^2 T}{\kappa}$ • $ZT \sim 3$, for applilcation, Now $ZT \sim 1$
    - Now focusing on heavily doped narrow-band semiconductors, $n \sim 10^{19} - 10^{20}/cm^3$, Not promising because of W-F law • Minimize phonon thermal conductivity $\Rightarrow$ Low Dimension, Amorphous, Nano-materials • Bi_2Se_3 & Bi_2Te_3: Quasi-2D system (Quintuple-layer) • Future focus: Considering Spin, Strong-correlation system

11. Magnetic Field: • Free electron gas: • No magnetoresistance • Hall coefficeint: $R_H = \frac{1}{ne}$
• Hall angle: $\tan\theta = \frac{E_y}{E_x} = \frac{Be\tau}{m} = \omega_c\tau$ • Quantum oscillations: $\omega_c\tau \gg 1$, Shubnikov-de Haas oscillations

12. Thermo-magnetic Transport: • Thermal Hall effect: Heat current (x) produces ∇T (y)
• Nernst effect: $\nu = \frac{E_y}{\nabla T_x B_z}$, Powerful technique for novel metals & superconducting vortices in type-II superconductors

4 Metal Insulator Transition (MIT)

1. I-M Transition within Band Theory: • Doping: Donors & Acceptors ⇒ impurity bands
• Pressure: Structure change ⇒ Overlap ⇐ Tight binding model • Wilson transition

2. Mott Insulator: • Mott's Gedanken Experiment: Increase the distance between atoms: Smaller hopping integral (t) and carrier density (n)
• Thomas-Fermi Theory: A negative charge added to the Fermi Sea ⇒ $\delta V \Rightarrow \delta n = -D(\varepsilon_F)\delta V \Rightarrow \nabla^2(\delta V) = k^2\delta V$ • Yukawa Potential: $\delta V = \frac{e^2}{r}\mathrm{e}^{-kr}$ • Screening length: $\lambda = \frac{1}{k}$, $k = \sqrt{\frac{4me^2k_F}{\pi\hbar^2}} \propto n^{1/6}$ for 3D FEG • Good metals ⇒ Non-interacting FEG
• Mott Insulator: Coulomb energy cost will exceed the kinetic energy gain • Low dimensional materials with large lattice constant • IMT: Tune the U/W ratio; Change band filling by doping. • Pressure induced IMT: Lattice contraction at IMT ($\sim$ 0.2%) ⇐ Metallic bonds • Increase of m^* due to strong electron interaction in doped Mott insulator • Many transition metal oxides (TMO): Separated by O, small density; Inner d electrons, weak overlap
• The Hubbard Model: $H = -t\sum_{\langle i,j\rangle,\sigma} c_{i\sigma}^\dagger c_{j\sigma} + U\sum_i n_{i\uparrow}n_{i\downarrow}$, where $t = \int \varphi_j^* \left[V(r) - v_i(r)\right]\varphi_i dr$
$U = \int \left|\varphi_i(r_1)\right|^2 \frac{e^2}{r_{12}} \left|\varphi_i(r_2)\right|^2 dr$ 1st tern: Hopping tern, 2nd tern: on-site Coulomb repulsion tern
• Band split: $U > W$ (W is the width of the original band) • Energy gap: $E_g \sim (U - W)$
• Perovskite Structure: ABO_3 • A only donates electronic charge and stabilizes the structure • For electronic properties, the BO_6 octahedral is most relevant • $RNiO_3$ system: Charge transfer insulators: O's p orbits and Ni's d orbits strongly hybridized. gap ~ 10-30 meV • Bonding angle: W is the largest for straight bond ($Ni^{3+} - O^{2-} - Ni^{3+}$ 180°) and smaller in distorted case. • Becomes better insulator with increasing R atomic number (smaller radius, more twisted bond of $B - O - B$) • Different transition metal: Different d-electron configuration, Different $p - d$ hybridization, Different U • Different A ions: Different ion size, Different bonding angle, Different W • Substitution of A: Different carrier density • Extra O or O deficiency: Different hole concentration • Substitution of B: Different on site configuration • Different dimensionality
• Magnetic Structure: Most have Antiferromagnetically ordered ground state

- Typical Strongly Correlated Materials: Incompletely filled d or f electron shells with narrow bands
- Wigner Crystal: Crystal of electrons • Potential $\sim \frac{e^2}{r_0}$ Kinetic $\sim \frac{\hbar^2}{mr_0^2}$ • when r_0 is large

3. Anderson Localization • Dilute, Nonmagnetic Impurity, $T = 0$, The distribution of the interaction

   - The Spin Diffusion Puzzle: The relaxation time of donor electron spin is way longer at low concentrations
   - Electron Spin Resonance (ESR): Unpaired electrons, Resonance frequency $\rightarrow$ microwave ($9GHz$ for $0.3T$), challenging, Study electron spin dynamics. • Phase sensitive (lock-in) detector, The first derivative of absorption line.
   - The Anderson Hamiltonian: $H = \sum_i \varepsilon_i n_i + \sum_{i,j} t_{ij} c_i^\dagger c_j$ • $V = 0$, as ε_i is const, Tight-binding model • $t = 0$, Atomic orbitals at each site • $\frac{V}{W} \ll 1 \Rightarrow$ Impurity scattering of Bloch waves • $\frac{V}{W} > 1 \Rightarrow$ Localization
   - Mobility Edge: $\pm\varepsilon_c$: $0 < \frac{V}{W} < 1$, Separating localized and non-localized states • Tuned by changing the level of disorder. • MIT: ε_F tuned by doping level or pressure • Trait: • No energy gap in DOS near ε_F (Psesdogap) • The electron number need not be integer • Coulomb repulsion in unnecessary
   - ▶ Near the localization transition – Still Controversy
   - Mott's Minimum Conductivity: Localization transition is discontinuous. •$lk_F > 1$, $l \geq a$ •$\sigma_{min}^{3D} \approx \frac{1}{3\pi^2}\frac{e^2}{\hbar}\frac{1}{a}$
   - Scaling Theory: $\frac{\hbar}{e^2}G(L) = g(L) \approx \frac{\Delta E}{\Delta V}$ •$\beta(g) = \frac{\mathrm{d}\ln g}{\mathrm{d}\ln L}$ • The transition is continuous •$\beta(g_c) = 0$, $g_c \Rightarrow$ Unstable fixed point • $g_0 > g_c \Rightarrow$ Conductor; $g_0 < g_c \Rightarrow$ Insulator • No extended states for any degree of disorder in 1D and 2D. • Doesn't consider other effects can destroy the localization (Magnetic field, S-O coupling, E-E interaction ...)
   - Weak Localization: $l \ll l_i < L < \xi$, where l is for elastic scattering, l_i is for inelastic scattering, L is the sample's scale, ξ is the localization length , $k_F l \gg 1$ • Self-crossing loops: $P = |A_1 + A_2|^2 = 2 \times 2|A|^2$, decreases the conductivity, Localization • Dephasing length: τ_ϕ , Loss of phase coherence will destroy weak localization

$$\frac{\delta\sigma}{\sigma} = -\gamma_d \begin{cases} \left(\frac{\tau_\phi}{\tau}\right)^{1/2} & = T^{-\eta/2} & ,d = 1 \\ \hbar \ln\left(\frac{\tau_\phi}{\tau}\right) & = \frac{\eta\hbar}{2}\ln\frac{\hbar}{k_B T} & ,d = 2 \\ \hbar^2\left(\frac{\tau_\phi}{\tau}\right)^{-1/2} & = \hbar^2 T^{\eta/2} & ,d = 3 \end{cases}$$

   - Wave Property: Reported for light waves, microwaves, sound waves, matter waves (BEC)
   - Non-interacting theory, hard to ideally realize in Solid

4. Charge Density Wave (CDW): (Lattice distortion induced)

   - Peierls' Theorem: 1D materials are insulating • The distortion of lattice opens an energy gap around the original E_F • The lattice distortion induced a CDW with $\lambda = \frac{\pi}{k_F}$, $k = 2k_F$, $\frac{\lambda}{a}$ can be irrational • Mechanism: e-ph coupling an electron-hole pair is created by a phonon • Kohn Anomaly: Electron-phonon interaction has a strong influence on the phonon spectrum near $q = 2k_F \Rightarrow$ Phonon softening • 1D, Phonon Frequency can drop to 0 • Hamiltonian: $H = \sum_{k,\sigma} \varepsilon_k c^\dagger_{k,\sigma} c_{k,\sigma} + \sum_q \hbar\omega_q b^\dagger_q b_q + \sum_{k,\sigma,q} g(k) c^\dagger_{k+q,\sigma} c_{k,\sigma} \left(b_q + b^\dagger_{-q}\right)$

• CDW gap: $\Delta = 2W\mathrm{e}^{-1/g}$ • CDW transition T: $T_P = \frac{\Delta(0)}{1.76k_B}$, From BCS theory

• TTF (donor)-TCNQ (acceptor): • MIT: σ drops at $55K$ and $38K$ (superstructure with $3.4a$), has a thermal activation behavior ⇒ Energy gap • Kohn anomaly: Neutron inelastic scattering • Fermi Surface Nesting: two pieces of parallel FS • Quasi-1D: FS as parallel planes ⇒ Warped, Still has FS nesting

• Pressure: Pressure ↑→ T_{CDW} ↑ ⇐ Imperfect nesting

• $NbSe_3$: • Two sharp increases of ρ at $144K$ and $59K$, remains metallic down to $T = 0$

• 3 types of chains, 2 successive Peierls trasitions

• $NbSe_2$: Layered structure, can be grown to extremely high quality • A superstructure with $3a$

• CDW state below $33K$ while being metallic, Superconductor below $7.2K$ • Multiband material

5. Jahn-Teller Theorem:

   • Non-linear degenerate molecules cannot be stable. • Change of electronic structure ⇒ MIT

   • Energy Gain: Electronic • Energy Cost: Elastic, Hund's rule coupling

   • Octahedral complexes of the transition metals: Elongation along z, Lower d_{z^2}, Upper $d_{x^2-y^2}$

   • K_xC_{60} Monolayers: MIT From K_3C_{60} to K_4C_{60} •Electrons in the LUMO orbital interact with certain vibrational mode of the C_{60} molecule and cause a permanent molecular distortion

5 Low Dimensional Electron Systems

1. The Motion of Microscopic Degrees-of-freedom

2. Examples:

   • Quasi-2D: • Giant magnetoresistance in multilayer magnetic films • High T_c superconductivity in layered copper oxides

   • 2D: • QHE in semiconductor MOSFET • Fractional QHE in semiconductor heterostructures

   • Quasi-1D: • CDW in TTF-TCNQ and $NbSe_3$

   • 1D: • Luttinger liquid in semiconducter nanowires • Carbon nanotubes

   • 0D: • Quantum dots • Molecular electronics and magnetism

3. Affect Propagation of waves and Formation of ordered phases

4. Susceptible to defects and thermal fluctuations

5. Electron DOS shows quantized behavior

6. Surface and Interface:

• Surface is a special type of interface

• Why? : • Break the periodicity in one dimension • Ideal for low-dimensional systems • Information and electronics industries heavily rely on • Surface catalysis can greatly increase the rate

• Surface structure: • Techniques (Surface sensitive): LEED, RHEED, SXD • Surface relaxation: May extend several layers • Surface reconstruction: Si (100) -- dimer rows , Si (111) -- 7×7 superstructure , Au (111) -- $22 \times \sqrt{3}$ superlattice (hcp & fcc) Mechanism: Minimization of surface free energy Semiconductors: Surface healing process $\rightarrow$ Reduce dangling bonds Metals: Formation of denser packing $\rightarrow$ Maximize the surface metallic bonding

• Surface Electronic Structure: • Parallel: Bloch waves • Perpendicular: Extended Bloch wave within the crystal, Exponentially decaying tail outside the surface • Surface state energy may lies within the bulk gap $\Rightarrow$ Surface electronic state, for both semiconductors and conductors (specific directions) • Energy: $E_s = E_0 + \frac{\hbar^2 k_\parallel^2}{2m^*}$

• Applications: Surface catalysis

• Creation: • Cleaving method: Materials with Van der Waals force between layers, In ultrahigh vacuum (UHV) environment

6 Others

1. Topological Insulator: • Single electron model • Mainly spin-orbit interaction

2. Superfluidity: • Liquid He-4 & He-3: Low boiling T $\Leftarrow$ Weak van der Waals force & low atomic mass

   • He-4 (Boson) < 2.17 K (BEC), He-3 (Fermion) < 2.49 mK (BCS)

3. Diamond: Indirect band gap: $E_g = 5.5\ eV$, good insulator

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