Superconductivity and Low Temperature Physics 2

Typical questions for the oral exam

Introduction

1. What is the typical temperature scale for low (and ultra-low) temperature phenomena?
2. What are typical low temperature phenomena and why do they only appear at low temperatures?
3. Who was the founder of low temperature technology at TUM?
4. What have been important discoveries in low temperature physics triggering new research fields?

Quantum Liquids & Fluids

Basic Aspects

1. What happens if you cool down a gas of non-interacting bosons?
    a. If there is a phase transition at low T, what drives the phase transition?
2. Who was predicting Bose-Einstein-condensation in about what year? When did experimentalists first succeed in realizing a Bose-Einstein condensate?
    a. Why did it take so long between theoretical prediction and experimental realization?
3. Nomenclature:
    a. What is a classical, what a quantum gas?
    b. What is a classical, what a quantum liquid?
4. Could you derive the expression for the de Broglie wavelength λ_T?
5. What is the average distance d of particles in a gas and how does it depend on pressure and temperature?
6. How is the ration λ_T/d in a gas on non-interacting particles change when we are reducing the temperature?
    a. What happens at $\frac{\lambda_T}{d} = 1$?
    b. What is the momentum and energy/temperature uncertainty related to the length scale d?
    c. What are the typical values for a free (non-interacting) electron gas and a gas of 4He atoms with $d \sim 1$ Å? Why are these values so different?
7. Bosons and fermions:
    a. What is the spin of bosons and fermions?
    b. If we are exchanging the position of two bosons (fermions), how does they many-particle wave function describing a gas of non-interacting bosons (fermions) change?
8. What is the number of possibilities to put two bosons/fermions/classical particles (1,2) in two quantum states A and B? What is the probability for the double occupancy of state A or B?
9. Could you sketch the Bose-Einstein, Fermi-Dirac and Maxwell-Boltzmann distribution?
10. What are well-known quantum fluids?
    a. What are the typical transition temperatures from a classical to a quantum fluid?
    b. What determines this characteristic temperature?

Helium

11. Discuss the key similarities and differences of the helium isotopes 4He and 3He.
    a. Where do we get 3He from?
12. Discuss the van der Waals bonding between He atoms:
    a. What are the key parameters determining the bonding strength?
    b. How does the potential energy depend on the distance between the atoms?
    c. What kind of crystal structure do you theoretically expect for a van der Waals crystal? What do we observe experimentally?
    d. Why are zero-point fluctuations important for 4He? What is the typical magnitude of position fluctuations?

e. What are the consequences of the quantum fluctuations for the properties of 4He?
f. Why does 4He no become solid at ambient pressure?

13. Could you sketch the phase diagram of 4He?
    a. What is thew slope of the $p(T)$ melting curve? What can you learn from the sign of the slope?
14. Could you sketch the phase diagram of 3He?
    a. What is the key differences between 4He and 3He? What are the key reasons for these differences?
15. Could you sketch the specific heat of 4He as a function of temperature close to the λ-transition?
    a. What would you expect for a system showing a 1^{st} order phase transition?
16. Could you sketch the specific heat of 3He as a function of temperature?
    a. What causes the pronounced difference between 4He and 3 He?

Ideal Bose gas

17. Sketch the particle distance and de Broglie wavelength with decreasing temperature?
    a. What happens if the particle distance d is about equal to the de Broglie wavelength λ_T?
    b. At what temperature do we obtain $d \sim \lambda_T$?
    c. What kind of cooling techniques can we apply?
18. How do we determine the inner energy of a gas of N non-interacting bosons?
    a. What is the occupation probability of a particular state?
    b. How can we avoid negative occupation probabilities?
19. What do we obtain for the particle density $n = N/V$ as a function of T and the chemical potential μ?
    a. What is the problem if we are reducing the temperature?
    b. How do we define the Bose-Einstein condensation temperature?
    c. How does the chemical potential vary as a function of temperature?
20. Below the Bose-Einstein condensation temperature:
    a. What is the theoretically expected ratio between the particle number in the ground state and the total particle number and how does it vary with temperature?
    b. Is the theoretical prediction seen in experiment? If no, what are the reasons for deviations?
21. Compare the temperature dependence of the inner energy of a classical particle gas and a quantum gas of bosons.
    a. What do you expect for the specific heat?
22. How can we realize a Bose-Einstein condensate? Why do we see differences between experimental results and theoretical predictions?
23. Could you discuss the key features of a Bose gas with finite interactions?

4He as a Bose gas

24. How does the radial distribution function in a Bose gas without any interactions look like and what do we measure for 4He?

25. What is the superfluid fraction for 4He? Could you give a plausible argument why the superfluid density is well below the total particle density?

Superfluid 4He

1. Describe the two-fluid model:
    a. How can we describe the superfluid component?
    b. What drives the superfluid component?
    c. How can the temperature dependence of the superfluid component be measured?
2. If we describe the superfluid component by a macroscopic wave function, what are the consequences for the curl of the velocity field? What are the experimental consequences?
3. What kind of phenomena can we observe when we cool down liquid 4He below T_λ?
    a. What do we observe for the viscosity? Why do different experimental approaches yield different results?
4. What is the physical explanation for the superfluid film flow? Are there any consequances for experimental setups?
5. Could you explain the thermomechanical effect? What is the fountain effect?
6. What is first and second sound in superfluid 4He? How could you generate and detect second sound in superfluid 4He?
7. Does the formation of a condensate automatically result in superfluidity?
    a. What would you expect for an ideal Bose-Einstein condensate of non-interacting bosons?
8. What kind of excitation spectrum do we need to obtain a non-vanishing superfluid velocity?
    a. What was the guess of Landau and Feynman?
    b. What are phonon- and roton-like excitations?
    c. How can we derive the critical superfluid velocity from the excitation spectrum?
    d. Could you give plausible arguments for the observed shape of the excitation spectrum?
9. What do we expect for the specific heat and thermal conductivity of superfluid 4He?
    a. At very low temperatures
    b. At intermediate temperature
    c. Close to T_λ

Vortices in superfluid helium

1. What is a vortex? What is its circulation?
2. Why is the circulation of the superfluid component in 4He quantized? What is the quantum of the circulation (vorticity)?
3. Compare vortices in superfluid helium to vortices in the mixed state of a superconductor:
    a. What are the corresponding quantities?
    b. What do we have to do to generate vortices in superfluid helium?
    c. What is the typical size of the vortex core?
    d. Is it energetically more favorable to generate a single vortex with the vorticity 2 or two vortices with vorticity 1?
4. How does the number of vortices scale with the angular velocity of a rotating helium container?

5. How can one image vortices in superfluid helium?

3He as a Fermi gas

1. Discuss the basic differences between a gas of non-interacting 3He and 4He atoms
2. What are the characteristic parameters of a gas of non-interacting Fermions?
    a. Do we observe difference between 3He and am ideal Fermi gas? If yes, what is the origin?
3. How does the temperature dependence of the specific heat and magnetic susceptibility look like?
4. Discuss the $p - T$ phase diagram of 3He
    a. What is the Pomeranchuk effect and how can we use it for cooling?
    b. What is the T-dependence of the entropy in the solid and liquid phase of 3He?
5. Discuss the origin of the superfluid state of 3He. How does the phase diagram look like?
    a. How many superfluid phases can we observe?
    b. How do we detect them in experiment?
6. What is the symmetry of the wave function of pairs of fermions? What kind of combinations of orbital and spin wave functions do we have?

Mixtures of 3He and 4He

1. Why are mixtures of 3He and 4He interesting from the basic physics point of view?
2. Discuss the temperature vs. 3He concentration phase diagram
3. Discuss the phase diagram of two substances A and B: When will we have complete miscibility and when complete phase separation?
4. Why do we have a miscibility gap when we are mixing 3He and 4He?
5. How can we make use the fact of the finite miscibility gap for dilution cooling?
6. Which parameters determine the cooling power of 3He/4He dilution refrigerators?

Quantum Transport in Mesoscopic Systems

Characteristic Length, Time and Energy Scales

1. What are microscopic, mesoscopic and macroscopic systems?
2. What is the definition of the Fermi wavelength, the mean free path and the phase coherence length in a metal/semiconductor? What are typical values?
3. Why do we have to study mesoscopic systems usually at low temperature?
4. How is inelastic scattering affecting the phase coherence time τ_φ?
5. What is the typical level spacing of electronic levels in a metal with size L?
6. How can we reduce the dimensionality of a metal from 3D to 2D, 1D and 0D?
7. How does the DOS look like in a 3D, 2D, 1D and 0D metal?
8. What is the Thouless energy, what is its meaning and how does it depends on the length of a piece of metallic conductor?

Description of Electron Transport by Scattering of Waves

9. How can we describe electrons in a metal by waves?
10. How is the dispersion of the electronic states look like for a 1D metallic conductor?
11. How can we describe tunneling through a barrier in the wave picture? How does the transmission probability depend on the barrier thickness?
12. How can we describe transport through an ideal conductor (ballistic, no scattering sites) in terms of open and closed channels?
13. If we have a conductor with N open transport channels, what is the conductance of this conductor? How would you calculate the conductance?
14. If you have a ballistic conductor connected to two reservoirs, where is the resistance coming from? What is the chemical potential within the ballistic channel?
15. How can you describe a non-ideal conductor containing scattering sites?
16. What is the difference between the scattering and the transfer matrix approach?
17. What kind of general properties do we usually have for a scattering matrix and where do they originate from?
18. If you compare the transport through an ideal ballistic conductor and a conductor containing scattering sites, what is the difference in the expression for the conductance?
19. How can you extend the simple case of a two-terminal conductor to one with many leads?
20. When you consider the passage of electrons through a particular part of a conductor on the time scale, what would you observe?
21. If the transport of the individual electrons is not correlated, what would be the probability to find N electron in the considered piece of the conductor?
22. What is the variance of N and how does this translate into current fluctuations?
23. What is shot noise and under which conditions can we observe it? What is the Fano factor?

Description of Electron Transport by Scattering of Waves

24. Discuss the transmission probability of an electron wave form A to B through a double slit? What do we expect for the transmission probability P_{AB}?
25. What is the acquired phase along a particular path from A to B?
26. What is a geometric, dynamical, and Aharonov-Bohm phase?
27. Discuss the transmission of an electron wave through a double tunnel barrier. What would you expect classically?
28. How can you describe the transport through the double tunnel junction by the scattering matrix approach? What are you expecting for the transmission probability?
29. What are transmission resonances?
30. How can you describe the Aharonov-Bohm effect in a normal metal ring by a scattering matrix approach?
31. What is the difference between universal conductance fluctuations and Altshuler.Aronov-Spivak oscillations?
32. What is weak localization and what is its origin?
33. What is the requirement for the observation of weak localization and what do you expect when you are switching on a magnetic field?
34. What are universal conductance fluctuations and what is their origin?
35. How can you study universal conductance fluctuations and why can you observe them only at low T and mesoscopic sample dimensions?

Coulomb blockade

36. Discuss the energy required to put an extra charge on a small piece of metal. How does this energy compare to the level spacing of the electronic states?
37. How would you calculate the electrostatic energy of a metallic island capacitively coupled to several gate voltages?
38. Discuss the simple case of a single island capacitively coupled to a source and drain electrode. What di you expect for the current flow as a function of the source and drain voltage?
39. What happens if you add a third gate electrode? What do you expect for the current flow (conductance) when you are varying the gate voltage at small source-drain voltage?
40. Under which conditions do we get a (Coulomb) blockade of current transport?
41. What are “Coulomb diamonds”?
42. What are the experimental preconditions to observe the Coulomb blockade effect?
43. How can we use the Coulomb blockade effect to construct a sensitive electrometer?

Generation and Measurement of Low Temperatures

Generation of Low Temperatures

1. Why was the liquefaction of gases important for low temperature physics?
2. What have been important applications of cooling machines in Bavaria?
3. What is the general scheme of cooling machines based on gases as working medium?
4. Can we liquify gases by compression? If yes, what are the requirements?
5. Can you explain why a gas is cooling down when it moving a piston?
6. When we do an adiabatic expansion of a gas, what relation holds between pressure and volume?
7. Describe a Carnot cycle in the $p - V$ phase diagram
    a. What is a heat pump and what is a heat engine?
    b. What is the efficiency?
8. Could you describe the Brayton method used, e.g. for the liquefaction of air?
9. Why are often turbine engines instead of piston-based engine used for cooling down and liquefying gases?
10. What is a regenerative machine and why do we need a regenerator?
    a. Discuss typical regenerative machine (e.g. Stirling, Gifford-McMahon or pulse tube refrigerator)
11. Discuss the Joule-Thompson process
    a. Can we cool an ideal gas by this process?
    b. Why is a gas cooling down in a Joule -Thompson process?
    c. What is the Joule-Thompson coefficient?
    d. What is the inversion temperature of a gas? What properties of the gas determine this quantity?
12. When we have two bottles of compressed nitrogen and helium gas, how can we find out which bottle contains what kind of gas without any gas detector?
13. How does evaporation cooling work?
    a. What kind of properties do we need to achieve ahigh cooling power?
    b. Compare liquid 3He and 4He.
14. What is the general operation scheme of a 3He/4He dilution refrigerator?
    a. Discuss the cooling power
    b. Why do we need an elevated still temperature?
15. How does adiabatic demagnetization cooling work?
    a. What determines the cooling power and the minimum achievable temperature?

Measurement of Low Temperatures