CHALMERS TEKNISKA HÖGSKOLA 2001-12-17
GÖTEBORGS UNIVERSITET Kl: 8.45-12.45
Fysik och teknisk fysik Sal: ML8

Tentamen i LÅGTEMPERATURFYSIK för F, GU och forskarstuderanden

Lärare: Tord Claeson, tel 772 3304

Hjälpmedel: Tefyma, Physics Handbook, Stand Math Tables och liknande handböcker, valfri räknedosa.

Answer 5 of the following problems. Motivate your answer in a logical way. You are welcome to illustrate with readable diagrams. Answer in Swedish or English.

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1. During the course you had the chance to participate in a mini-symposium on Bose-Einstein condensation with talks by Nobel prize winners 2001 and 1997

(a) What is a Bose-Einstein condensation? For what particles, when and under what conditions does it occur? The superfluid state in ^{4}He may be considered as a Bose-Einstein condensate. What are the properties of the atoms of the condensate? How does it differ from a condensate of an ideal <u>gas</u> of atoms? What is the temperature dependence of the density of the condensate? ^{3}He and superconductors can also be considered as Bose-Einstein condensates despite the fact that those atoms and electrons are fermions. Why? Discuss the symmetries of the wave functions describing the condensed states in ^{3}He and superconductors. (2p)

(b) It has been possible to observe Bose-Einstein condensation of, e.g., H, Rb, Na, and Li atom gases at very low temperature. This gave the 2001 Nobel prize of physics. Describe the condensate, e.g., number of atoms, size, temperature, confinement, lifetime. What happens if two condensates are put in contact to each other? How does a gas Bose-Einstein condensate differ from a superfluid? (2p)

2. In order to study phenomena like Bose-Einstein condensation or nuclear magnetism, it is needed to cool samples to the microkelvin to nanokelvin temperature range. A couple of experimental methods have been used to reach such low temperatures.

Discuss one of the methods (of your choice) to reach such low temperatures in the μK to nK range. Describe the principle of cooling, the experimental set up and possible materials, cooling procedure, possible pre-cooling, thermal equilibrium, limiting temperature and cooling capacity. Any difficulties in reaching thermal equilibrium? How do you define the temperature of the system and suggest a way to measure it. (4p)

3. From home problems: Compare properties of superfluid helium and superconductors. One example: Quantized vortices appear in superfluid ^{4}He that is rotated with a frequency $f>f_{crit}$. Similarly, quantized fluxons appear in a type II superconductor for $H>H_{c1}$. Show that the circulation and the magnetic flux are quantized and discuss under which conditions the phenomena occur. Suggest different ways of measuring vortices and fluxes. What results are obtained? Try to make a somewhat general discussion.(4p) Plus question: Can vortices also exist in Bose-Einstein condensates?

4. Two superconducting Josephson junctions with critical currents I_{c1}= 0.5 mA and I_{c2} = 0.7 mA are connected in parallel. The total current through both junctions is I = 1 mA and no external magnetic flux is applied. Find the current through each junction under the assumption that the inductance of the loop, formed by the two junctions and its connections, is small. What happens if the total current exceeds 1.2 mA? Sketch I-V curves as a function of applied magnetic field. (4p)

5. Theory of superconductivity.

(a) Give a short description of the BCS (Bardeen-Cooper-Schrieffer) theory of superconductivity. What are the main assumptions, approximations, and results of the theory? (3p)

(b) It is possible to describe both the superconductors and superfluid ^{3}He within the BCS theory. Discuss the differences between "conventional" (low-T_c) superconductors and the phases of superfluid ^{3}He within the contexts of the BCS theory (e.g. interactions leading to pairing, symmetries of wave functions (superconducting order parameter or gap function) and energy gaps). (1p)

6. High T_C superconductors. Field effects.

During a symposium you have got a lecture regarding field effect doping of organic molecules and cuprates leading to superconductivity at high temperature (B.Batlogg, Nobel Symp. Dec. 01). p-doping of intercalated C60 films lead to a T_c close to 120 K. Starting from the so called infinite layer superconductor $CaCuO_2$ it was possible to both n- and p-dope the layers by applying an electric field between a gate structure and the film. This gave a maximum T_c at a certain n- or p-doping.

Discuss what phases, relatively doping x, that are typical of a cuprate superconductor and indicate relevant critical temperatures vs. x.
What can you say regarding a high T_c superconductor regarding
- charge carrier density?
- pair interaction?
- symmetry of the gap function?

Compare typical lengths (penetration depth, coherence length) with those of a "conventional, low-T_c superconductor. Comment on possible anisotropy. (4p)

6. You have studied a newly proposed primary thermometer during a laboratory exercise.

(a) What is characteristic of a primary thermometer? How does it differ from a secondary thermometer (list characteristic properties for the latter as well)? (1p)

(b) Discuss "single electron tunneling". What are the conditions that have to be met in order to observe the phenomenon? What are the main features? What is meant by Coulomb blockade? How can the phenomenon be used to measure small shifts in the charge distribution? (3p)

7. Assume that you want to deposit a thin film upon a glass that is cooled by a heat reservoir at 1 K. The glass substrate is 2 mm thick, has an area of 1 cm^2 and “sees” a black body at room temperature through a hole that also can be considered to be 1 cm^2. What temperature do you expect at the surface of the glass if you assume that its back side is at 1 K? The average thermal conductivity of the glass can be considered as λ=0.0002 W/cm^2K within a temperature range of 1 to 2 K, λ=0.0006 W/cm^2K within a temperature range of 1 to 4 K, λ=0.001 W/cm^2K within a temperature range of 1 to 20 K. The emissivity of the glass is 0.9, Stefan´s constant $\sigma = 5.67 \times 10^{-12}$ W/cm^2K^4. The accomodation coefficient of He on glass is about 0.67 at 10 K, 1 below 4 K. The pressure is assumed to be $<10^{-10}$ torr (mainly helium gas remaining). ($dQ/dT \approx$ const.x a_oxp_{mm}xΔT W/cm^2, where const.$\approx$0.028 for He.) Suggest some measures to decrease the temperature at the substrate surface. (4p)
Plus questions: How would you check the temperature at the surface? How do you cut down the heat leak along the electrical leads to the film?

8. Short questions to test the understanding of concepts. Give short descriptions or definitions (use diagrams if appropriate) of the following:

(a) Sketch the phase diagram (p-T) of liquid ^{3}He, in particular in the range of about 1 mK <T<3 mK, denote different phases and list their most characteristic properties.

(b) What is second sound in a superfluid? What is roughly the value of the velocity of 2nd sound at 1.5 K in ^{4}He?

(c) What is photon or phonon stimulated tunneling in a superconducting tunnel junction?

(d) What is the relation between frequency and voltage in the ac Josephson effect?

(e) What is the current distribution over the length of a Josephson junction in a magnetic field that is applied within the plane of the junction and perpendicular to the direction of the current? The length of the junction is assumed to be no longer than the Josephson penetration depth.

(f) What is the current distribution over the length of a Josephson junction in a magnetic field that is applied within the plane of the junction and perpendicular to the direction of the current? The length of the junction is assumed to be considerably larger than the Josephson penetration depth.

(g) What is the Josephson penetration depth? What determines its value?

(h) What is the London penetration depth? What determines its value? What is the minimum ratio between the London penetration depth and the coherence length in a type II superconductor?

(i) Sketch the low temperature phase diagram (T vs concentration) of a ^{4}He-^{3}He liquid mixture. Give most important temperatures and concentrations of the phase diagram for the functioning of a dilution refrigerator.

(j) What is a quantized circulation (vortex) in sueprfluid helium? Value? Similarly, what is a quantized flux (fluxon) in a superconductor and what is its value?

(0.5p per sub-problem, max 4p)