CHALMERS TEKNISKA HÖGSKOLA — 2000-12-06
GÖTEBORGS UNIVERSITET — Kl: 8.45-12.45
Fysik och teknisk fysik — Sal: TL1

Tentamen i LÅGTEMPERATURFYSIK för IMP(F), F, Kf, GU och forskarstuderanden

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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. We have come across the concept of Bose-Einstein condensation (BEC) several times within the course.

(a) What is a Bose-Einstein condensation? For what particles, when and under what conditions does it occur? The superfluid state in ^{4}He is considered to be a Bose-Einstein condensate. What are the properties of the atoms of the condensate? How does it differ from a condensate of an ideal gas of atoms? What is the temperature dependence of the density of the condensate? ^{3}He and superconductors can also be considered as some kind of Bose-Einstein condensates despite the fact that those atoms and electrons are fermions. "Quasi-bosons" are formed by pairing the fermions. What is characteristic of the constituents that form the pairs? I.e. discuss the symmetries of the wave functions for the pairs in ^{3}He and superconductors. (2p)

(b) Superfluid ^{4}He can be described by a two-fluid model. Give a short account of that model. You may consider the superfluid and normal parts of the fluid as a condensate and excitations from the condensate. Discuss the properties of the condensate and the excitations in superfluid ^{4}He. Can you describe a superconductor or ^{3}He in a similar model? What are the properties of the two "fluids" in those cases? (2p)

2. It has lately been possible to observe Bose-Einstein condensation of H, Rb, Na, and Li atom gases at very low temperature. It was recently reported (GP, Nov 26, 2000) that a new low temperature record has been obtained in Helsinki cooling nuclei in Rh. This problem centers on how to obtain ultra-low temperature. You have a choice of either discussing laser cooling or adiabatic demagnetization of nuclear spins.

(alt.a) Discuss mechanisms of laser cooling. Why can one cool (slow down) atoms by shining light on them? How does the Doppler effect come in? One would expect a lowest temperature of $T_{Doppler}=\hbar\Gamma/2k_B$ where Γ is the width of the absorption peak (equal to the natural width of the excited state) and at a detuning of $\delta=-\Gamma/2$. However, one has obtained temperatures well below this value and at detunings much larger than the presumed optimal value. One method for further cooling is the polarization gradient cooling (or Sisyfus cooling). Describe that method. One would then expect a lowest temperature to be the one corresponding to the recoil limit. What is that? Even lower temperatures can be reached, for example by using the Velocity Selective Optical Pumping method that selects atoms with velocity zero that do not absorb light and remain cold (dark state). Once slowed down, the atoms can be trapped. One has trapped atoms in, e.g., magneto-optic traps and decreased their energy further by evaporative cooling. Explain the principle of a magnetic trap for neutral atoms. What is evaporative cooling? Which is roughly the lowest temperature that has been reached by laser cooling? Illustrations are welcome. (4p) (alt.b) Very low temperatures have been achieved using adiabatic demagnetization of nuclei spins. Describe the method: principle, materials used, cooling procedure, pre-cooling, cooling capacity. What are the difficulties in obtaining thermal equilibrium? What are the lowest temperatures that one has reached with the cooling method in respect of cooling down an independent sample and the spin system itself, respectively? What can the ultra-low temperatures be used for? I.e. give examples of properties that can be studied. (4p)

3. Two 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? (4p)

4. High T_c superconductors. During a laboratory session you studied intrinsic tunneling properties of high temperature superconductors. This problem concerns properties of these ceramic superconductors.

(a) Discuss the lattice properties that are typical of the high- T_c superconductors. What characterizes the crystal structure? Anisotropy? What constituents are important? (1p)

(b) Compare characteristic superconducting properties of the high T_c superconductors with "conventional" ones (low- T_c superconductors). (You can, for example, compare T_c, B_c, coherence length, penetration depth, charge carrier type and density, symmetry of pair wave function, pairing mechanism, or other properties) (1.5p)

(c) What are the tunneling properties that you can measure in a high-T_c superconductor? What are the differences compared to low- T_c ones? How can an experiment be performed? (1p)

(d) Superconducting magnets based upon a coil of Nb3Sn, connecting leads of a bismuth cuprate (high temperature) superconductor (from the coil towards room temperature) and a mechanical cooling machine giving 10 K are now being offered commercially. Why use the high T_c superconductor in this combination? (0.5 p)

5. Vortices are typical of both superfluids and superconductors.

(a) Show that the circulation of fluid around a vortex in a superfluid is quantized. Show that the magnetic flux of a vortex in a superconductor (a fluxon) is quantized. (2 p)

(b) Discuss the flow of current and the distribution of magnetic flux density in a type-I and in a type-II superconductor, resp. What are the characteristic lengths and how do they compare? (1 p)

(c) Exceeding a critical rotation velocity or a critical magnetic field, a lattice of vortices will appear. Discuss the expected symmetry and methods to detect the vortices (fluxons) in the superfluid and the superconductor. (1p)

(bonus part) If you can discuss typical features of a vortex in superfluid ^{3}He, you can obtain an extra point within this problem to compensate possible deficiencies in other parts.

6. 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 $a_o x p_{mm} x \Delta T$ 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?

7. 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. (0.5p per sub-problem, max 4p)