UNIVERSITY OF LONDON

MSci EXAMINATION 2002

For Internal Students of

Royal Holloway

DO NOT TURN OVER UNTIL TOLD TO BEGIN

PH4502A: LOW TEMPERATURE PHYSICS AND NANOTECHNOLOGY

Time Allowed: TWO AND A HALF hours

Answer THREE QUESTIONS only

No credit will be given for attempting any further questions

Approximate part-marks for questions are given in the right-hand margin

Only CASIO fx85WA Calculators are permitted

GENERAL PHYSICAL CONSTANTS

Permeability of vacuum	μ_0	=	$4\pi \times 10^{-7}$	H $\mathrm{m^{-1}}$
Permittivity of vacuum	ε_0	=	8.85×10^{-12}	F $\mathrm{m^{-1}}$
	$1/4\pi\varepsilon_0$	=	9.0×10^{9}	m $\mathrm{F^{-1}}$
Speed of light in vacuum	c	=	3.00×10^{8}	m $\mathrm{s^{-1}}$
Elementary charge	e	=	1.60×10^{-19}	C
Electron (rest) mass	m_e	=	9.11×10^{-31}	kg
Unified atomic mass constant	m_u	=	1.66×10^{-27}	kg
Proton rest mass	m_p	=	1.67×10^{-27}	kg
Neutron rest mass	m_n	=	1.67×10^{-27}	kg
Ratio of electronic charge to mass	e/m_e	=	1.76×10^{11}	C $\mathrm{kg^{-1}}$
Planck constant	h	=	6.63×10^{-34}	J s
	$\hbar = h/2\pi$	=	1.05×10^{-34}	J s
Boltzmann constant	k	=	1.38×10^{-23}	J $\mathrm{K^{-1}}$
Stefan-Boltzmann constant	σ	=	5.67×10^{-8}	W $\mathrm{m^{-2}}$ $\mathrm{K^{-4}}$
Gas constant	R	=	8.31	J $\mathrm{mol^{-1}}$ $\mathrm{K^{-1}}$
Avogadro constant	N_A	=	6.02×10^{23}	$\mathrm{mol^{-1}}$
Gravitational constant	G	=	6.67×10^{-11}	N $\mathrm{m^{2}}$ $\mathrm{kg^{-2}}$
Acceleration due to gravity	g	=	9.81	m $\mathrm{s^{-2}}$
Volume of one mole of an ideal gas at STP		=	2.24×10^{-2}	$\mathrm{m^{3}}$
One standard atmosphere	P_0	=	1.01×10^{5}	N $\mathrm{m^{-2}}$

MATHEMATICAL CONSTANTS

$e \cong 2.718$ $\pi \cong 3.142$ $\log_e 10 \cong 2.303$

PART MARKS

Answer 3 questions only, including at least one question from section A and at least one from section B.

Section A

1. (a) What is a *quantum liquid*? **[5]**

   (b) Explain why helium remains liquid down to absolute zero, in the absence of a significant externally applied pressure. **[5]**

   (c) Describe the origin of the minimum in the melting curve of ^{3}He. **[5]**

   (d) Two Bose-Einstein condensates of identical alkali gas atoms (^{23}Na) are allowed to drift through each other at a relative velocity of $1\ \mathrm{cm\ s^{-1}}$. An optical experiment can measure the density as a function of position. Explain what you expect to observe, in as much detail as possible. **[5]**

2. (a) Describe the excitations and their dispersion relations for the following systems: **[10]**

   superfluid ^{4}He,

   an ideal Bose gas, confined within a box at a constant potential,

   normal ^{3}He,

   superfluid ^{3}He.

   (b) Derive the expression for the Landau critical velocity for superfluid ^{4}He Discuss its physical meaning, and explain why an ideal Bose gas cannot be superfluid. **[6]**

   (c) Explain the role of quantized vortex excitations in the dissipation of superflow. **[4]**

3. (a) Sketch the phase diagram of superfluid ^{3}He. Indicate the orders of the various phase transitions and describe the effect of an external magnetic field on the phases. **[5]**

   (b) The superfluid phases of the ^{3}He were first discovered by the appearance of several features in a pressure versus time trace in Pomeranchuk cooling experiments. Describe these features and explain why they appear as they do. **[5]**

   (c) Describe how NMR was used to identify that these signatures corresponded to phase transitions in the liquid. **[4]**

   (d) Discuss the Cooper pair wave functions of the A and B phases. **[3]**

   (e) Account for the NMR frequency shift in the A phase and the differing magnetization of the A and B phases. **[3]**

PART MARKS

Section B

4. (a) Describe the positive resist process for patterning a thin film using electron beam lithography. Describe briefly the phenomenon taking place during the exposure of positive resist with an electron beam. **[4]**

   (b) What are the main tools of "top-down" and "bottom-up" nanotechnology? Give three examples of "bottom-up" nanotechnology techniques. **[3]**

   (c) Explain the difference between isotropic and anisotropic etching processes used in lithography. What is the degree of anisotropy? Give an example of an etching technique with a high degree of anisotropy. **[3]**

   (d) Explain the mechanism for the proximity effect which occurs during electron beam lithography. Describe how corrections may be applied to minimise the results of the proximity effect. How may the sample configuration be altered to minimise the effect? **[5]**

   (e) Explain the physical meanings of the terms resist contrast, γ, and the sensitivity, D_T for a positive resist. **[5]**

5. A certain conductor has the shape of a strip with the dimensions of
   $L_x = 1$ μm in the direction of the electrical current,
   $L_y = 10$ nm and $L_z = 10$ nm in the transverse directions.

   The elastic scattering rate for the conduction electrons, $\tau^{-1} = 10^{15}$ s^{-1}; the phase breaking rate, τ_ϕ^{-1}, changes with temperature according to the law $\tau_\phi^{-1} = A\,T^3$ s^{-1}; $A = 10^8$ s^{-1} K^{-3}; and the Fermi velocity, $v_F = 10^6$ ms^{-1}, the concentration conduction electrons n = 10^{28} m^{-3}, electron mass m = m_o, m_o is the free electron mass.

   (a) Calculate the temperature at which the conductor reaches the mesoscopic regime. **[6]**

   (b) Using Drude's formula calculate the classical conductance of a conductor. **[5]**

   (c) Estimate the relative amplitude of the Universal Conductance Fluctuations, $\Delta G/G$, for the conductor. **[5]**

   (d) Describe four major electron scattering processes in metallic conductors and their influence on quantum interference effects. **[4]**

6. (a) Describe the principles of operation of the Scanning Tunnelling Microscope (STM) in Constant Current Mode (CCI) and in Constant Height Mode (CHI). What are the practical limitations of CCI which can be overcome using CHI? **[5]**

   (b) What physical effect is used in the scanning mechanism in the STM? **[3]**

   (c) What are the main conditions for observation of Coulomb blockade in single electron tunnelling in small junctions? **[5]**

   (d) What are the transverse dimensions of the tunnelling capacitor with the thickness d = 3 nm of insulating Al_2O_3 layer showing the Coulomb blockade at liquid nitrogen temperature of 77K? What is the threshold voltage? ($\varepsilon = 2$ for Al_2O_3) **[7]**

END