Exam Nanophysics and Nanotechnology – WBPH025-05

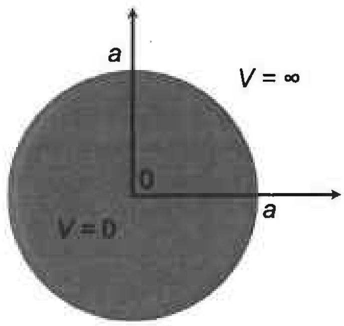
Monday, 27^{th} of January 2025, 11:45-13:45

READ THIS FIRST:

- This exam has a duration of 2 hours.
- Clearly write your name and student number on each answer sheet that you use.
- On the first answer sheet, write the total number of answer sheets that you turn in.
- You are not allowed to use any notes, books and mobile devices. You can use the calculator.
- Give clear descriptions of what you calculate, explain physical arguments wherever it is needed.
- The list of constants is given on the last page.
- The full exam is 100 points. Your grade for the exam is the total score divided by 10.

Problem E1.1 [12 points]
Briefy respond to the following questions
(a) [3 points] What is nanophysics and what is nanotechnology?
(b) [3 points] What is quantum confinement?
(b) [3 points] What is the condition for the size of quantum dot to make it quantum confined?
(c) [3 points] How can quantum confinement be used in technology?

Problem E1.2 [24 points]
To describe a carrier confined to a quantum dot, one can consider a model of a particle in a sphere, as schematically illustrated below.



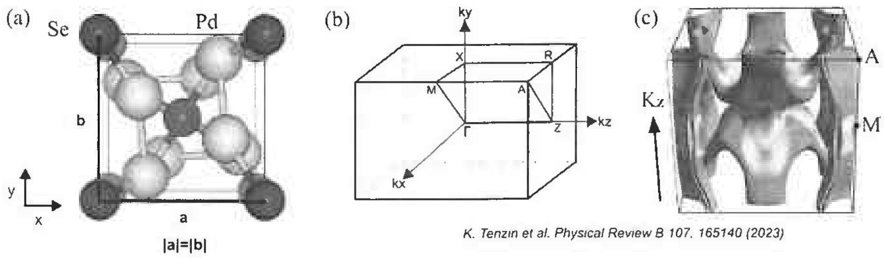
For a sphere of radius a, the lowest-energy solution of the corresponding Schrödinger equation is:

$$\psi(r,\theta,\phi) = N\frac{\sin(\pi r/a)}{r}$$

(a) [12 points] Find the normalization factor N.
(b) [12 points] Consider an electron trapped in this well. Calculate the probability of finding the electron inside an inner sphere of radius $a/2$. Assume the same lowest-energy solution.

Hint: The infinitesimal element of volume in spherical coordinates is $\mathrm{d}V = r^2 \sin\theta \; \mathrm{d}\phi \; \mathrm{d}\theta \; dr$.

Problem E1.3 [14 points]
The figure below shows properties of Pd_4Se calculated using density functional theory. Panel (a) presents the crystal unit cell, (b) Brillouin zone with the high-symmetry points, (c) Fermi surface. Using these data, respond to the following:
(a) [2 points] Specify the crystal system of the material. *Hint:* Use both panels (a) and (b).
(b) [2 points] How many inequivalent atoms does the unit cell contain?
(c) [2 points] Specify the atomic positions of the selenium atoms in the basis of the lattice vectors.
(d) [2 points] What is the Bravais lattice of the reciprocal lattice?
(e) [3 points] Specify the positions of all the high-symmetry points marked in the figure in the basis of the reciprocal lattice vectors. Note that the axes k_x, k_y, and k_z refer to the coordinates in the reciprocal space and are not the reciprocal lattice vectors.
(f) [3 points] Is the material metallic or insulating? Justify your answer.



K. Tenzin et al. Physical Review B 107, 165140 (2023)

Problem E1.4 [8 points]
Using an optical microscope, you observe two point sources that are separated by 270 nm on your sample. Their emission wavelength is $\lambda = 400$ nm. The microscope's objective possesses a numerical aperture NA = 1.3. Can you resolve the nanoemitters as distinct point sources according to the Rayleigh-criterion? Explain.

Problem E1.5 [22 points]
(a) [10 points] Compare scanning tunnelling microscopy (STM) and transmission electron microscopy (TEM). Compare them, describe how they work and explain if one of them provides advantages with respect to the other.
(b) [5 points] The feedback loop of an STM works to maintain a certain parameter constant. Which parameter is maintained constant? Explain how the instrument works.
(c) [7 points] The STM microscope can allow the measurement of DOS. Explain briefly how.

Problem E1.6 [20 points]
(a) [6 points] What is the difference between diamagnetism, paramagnetism and ferromagnetism?
(b) [10 points] Briefly describe the key differences between ferromagnets, ferrimagnets and antiferromagnets. Consider magnetization in the real space and the differences in the band stuctures.
(c) [2 points] What is the Curie temperature? What happens above the Curie temperature?
(d) [2 points] Name at least two devices utilizing magnetic materials.

NATURAL CONSTANTS AND UNITS

Speed of light in vacuum	c	299792458 ms^{-1} (exact)
Planck's constant	h	$6.62607015 \cdot 10^{-34}$ Js (exact)
Planck's constant in eV s	h	$4.136 \cdot 10^{-15}$ eVs
Planck's reduced constant	$\hbar$	$1.055 \cdot 10^{-34}$ Js
Planck's reduced constant in eV s	$\hbar$	$6.582 \cdot 10^{-16}$ eVs
1 electron volt (unit 1 eV)	eV	$1.602 \cdot 10^{-19}$ J
Electron charge	$-e$	$-1.602 \cdot 10^{-19}$ C
Electron mass	m_e	$9.109 \cdot 10^{-31}$ kg
Electron mass	m_e	0.511 MeV/c^2
Gyromagnetic ratio for orbital angular momentum of electron	γ	$-8.794 \cdot 10^{10}$ $s^{-1}T^{-1}$
Gyromagnetic ratio for spin of electron	γ_e	$-1.761 \cdot 10^{11}$ $s^{-1}T^{-1}$
Electron g-factor	g_e	2.002
Bohr magneton	μ_B	$9.274 \cdot 10^{-24}$ JT^{-1}
Atomic mass constant	m_u	$1.661 \cdot 10^{-27}$ kg
Proton mass	m_p	$1.673 \cdot 10^{-27}$ kg
Avogadro constant	N_A	$6.022 \cdot 10^{23}$ mol^{-1}
Bohr radius for H atom	a_0	$5.292 \cdot 10^{-11}$ m
Rydberg unit of energy for H atom in eV	R_y	13.61 eV
Boltzmann constant	k_B	$1.380649 \cdot 10^{-23}$ JK^{-1} (exact)
Electric permittivity of vacuum	ϵ_0	$8.854 \cdot 10^{-12}$ Fm^{-1}
Magnetic permeability of vacuum	μ_0	$1.257 \cdot 10^{-6}$ Hm^{-1}