Structure of Matter (NS-266B)

Exam

13 April 2015. Time: 17:00-19:00   (Please do not leave before 17:45)

The exam consists of two parts:
Exercises on Condensed Matter (Part I) and Subatomic Physics (Part II).

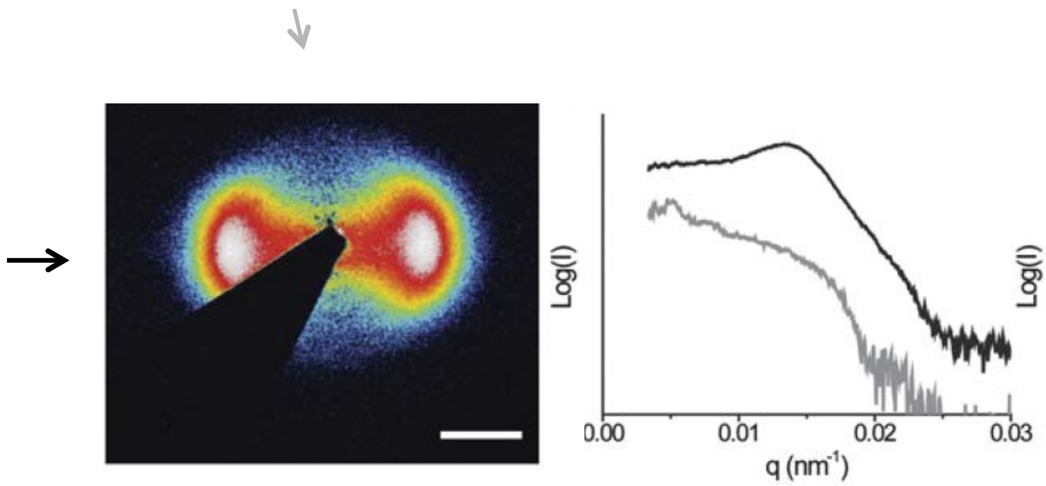
The maximal number of points is indicated for each exercise.
The total number of points is 102.

→ Answer each of the exercises on a separate piece of paper.
→ Write your name and student number on each page.
→ Do not give final answers only, explain your reasoning (short) and give full calculations.
→ Simple calculator use is allowed (no programmable)
→ No mobile/smart phone!

Good luck!

Part I – Condensed Matter

Exercise 1.1 (17 points)



Above you see the 2D scattering pattern of an aligned liquid crystal phase and two intensity line profiles. **Left:** Log of the scattered x-ray intensity versus scattering vector *q*, the white bar has a length of 0.01 nm^{-1} (note the black 'shadow' is the beam stop). **Right:** Averaged intensities taken in the direction of the two arrows left.

a) (7 points) From what soft matter phase is the 2D scattering pattern given above and mention the characteristics, which define this phase. Explain all features visible in the scattering pattern and give a schematic drawing of the liquid crystal oriented correctly with respect to the 2D scattering pattern and scattering beam direction.

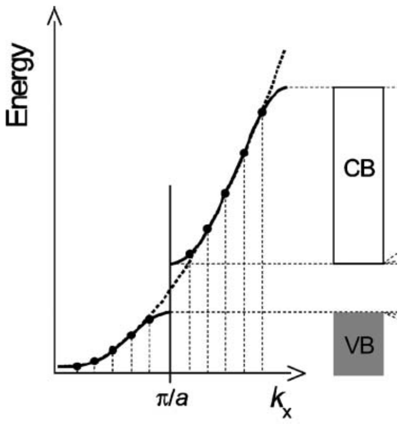
b) (5 points) Give a rough quantitative estimate of the dimensions of the scattering units that gave rise to the scattering, explain your reasoning.

c) (5 points) Could a liquid crystal for which the scattering pattern is given above be used in a liquid crystal display? Explain your reasoning by explaining how a liquid crystal display works.

Exercise 1.2 (10 points)

Constants: k_B = 1.38 x 10^{-23} J/K, $h/(2\pi)$ = 1.054 x 10^{-34} Js,
m_e = 9.11 x 10^{-31} kg, e = 1.60 x 10^{-19} C, ε_o = 8.854 x 10^{-12} F/m.

In the schematic figure shown on the right the electronic structure of both a macroscopic semiconductor (lines) and that of a cubic 5 nm length semiconductor ('quantum dot') are illustrated (thick dots).



a) (5 points) Explain through a calculation what roughly is the spacing in between the thick dots belonging to the quantum dot electronic structure.

b) (5 points) Could such modes for a quantum dot or a bulk semiconductor be imaged with a STM? Explain you answer by explaining how an STM works.

Exercise 1.3 (23 points)

a) (10 points) Explain with schematic diagrams, in which you also draw the energies of the bottom of the conduction band and the top of the valence band, what a *pn* junction is and explain how it can be realized in a silicon crystal.

b) (5 points) Explain why/how a *pn* junction can be used to rectify a current or, said in another way, why a *pn* junction acts as a diode.

c) (8 points) Intrinsic semiconductors (e.g. with a gap energy of 1 eV) have an unusual temperature dependence of the conductivity as compared to metals. Explain, using relevant formula's/derivation, what is the origin of this behavior and explain if you expect this behavior to also be present in an *n*-type semiconductor?

Part II – Subatomic Physics

Exercise 2.1: Multiple choice questions (20 points)

Instructions: Choose one answer. Each correct answer gives 2 point.

1. Which statement is wrong? Elementary particles

   A. have no structure.
   B. are point-like objects.
   C. have excited states.
   D. are the building blocks of matter.

2. The Standard Model of Particle Physics

   A. gives a description of the elementary particles and the interaction between them.
   B. gives a description of the elementary particles only.
   C. gives a description of the interaction of elementary particles only.
   D. describes the interaction between quarks only.

3. Which of the following properties cannot be directly measured with particle detectors?

   A. Specific ionisation energy loss.
   B. Time of Flight.
   C. Energy.
   D. Invariant mass.

4. Strange particles (e.g., lambda and kaons) provided evidence for a new force since they

   A. only exist in cosmic rays.
   B. are produced via the strong interaction but decay very slowly (relatively long life time).
   C. are produced via the electro-magnetic interaction but decay very slowly (relatively long life time).
   D. are produced via the strong interaction but decay very fast (relatively short life time).

5. Fundamental interactions

   A. are coupled to a certain particle property.
   B. are coupled to several particle properties.
   C. cannot be described by the exchange of particles.
   D. do not happen for anti-particles.

6. Which of the following particles are not colour neutral?

   A. Leptons
   B. Hadrons
   C. Mesons
   D. Quarks

7. Which of the following quantities is not necessarily conserved in particles reactions and decays?

   A. Lepton number
   B. Baryon number
   C. Strangeness
   D. Charge

8. The coupling constant α_s of the strong interaction

   A. is constant and bigger than the Hyperfine structure constant $\alpha = 1/137$.
   B. is constant and smaller than the Hyperfine structure constant $\alpha = 1/137$.
   C. depends on the momentum transfer between quarks and gluons.
   D. depends on the mass transfer between quarks and gluons.

9. The relevant particle property for the weak interaction is the

   A. baryon number.
   B. lepton number.
   C. charge flavour.
   D. quark flavour.

10. Quarks can be

   A. observed through their hadronisation into particle jets.
   B. observed as free objects.
   C. detected with hadronic calorimeters.
   D. detected through their trajectory in particle detectors.

Exercise 2.2: Conservation laws (20 points)

a) (2 points each) Check the following particle reactions and decays for violation of the conservation of energy/mass, electric charge, baryon number, lepton number and strangeness number (use the enclosed tables) say whether they are allowed or forbidden and why:

A) $p \rightarrow \pi^0 + e^+$

B) $e^- + e^+ \rightarrow \gamma + \gamma$

C) $K^0 \rightarrow \pi^+ + \pi^-$

D) $p \rightarrow e^+ + \Lambda^0 + \nu_e$

E) $\pi^- + p \rightarrow \Delta^0 + \pi^0$

F) $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

b) (4 points each) Write down the quark content of each particle for the following particle reaction and decay (see enclosed tables) and draw the Feynman diagram on quark level:

A) $\Delta^+ \rightarrow n + \pi^+$

B) $\pi^- + p \rightarrow \Lambda^0 + K^0_s$

Exercise 2.3: Mass/energy conservation and invariant mass method (12 points)

a) (6 points) When a beam of high-energy protons collides with protons at rest in the laboratory (e.g., in a container of water or liquid hydrogen), neutral pions (π^0) are produced by the reaction $p + p \rightarrow p + p + \pi^0$. Compute the threshold energy of the protons in the beam for this reaction to occur.

b) (6 points) A π^0 with energy 850 MeV decays in flight via the reaction $\pi^0 \rightarrow \gamma + \gamma$. Compute the angles made by the momenta of the gammas with the original direction of the π^0.

Note that $E^2 = (pc)^2 + (mc^2)^2$. The mass of the neutral pion is listed in table 12-3.

Table 12-3 Hadrons that are stable against decay via the strong interaction

Name	Symbol	Mass (MeV/c^2)	Spin ($\hbar$)	Charge (e)	Antiparticle	Mean lifetime (s)	Typical decay products*
Baryons							
Nucleon	p (proton) or N^+	938.3	1/2	+1	$\bar{p}$	$>10^{32}$ y	
	n (neutron) or N^0	939.6	1/2	0	$\bar{n}$	930	$p + e^- + \bar{\nu}_e$
Lambda	Λ^0	1116	1/2	0	$\overline{\Lambda}^0$	2.5×10^{-10}	$p + \pi^-$
Sigma	Σ^+	1189	1/2	+1	$\overline{\Sigma}^-$	0.8×10^{-10}	$n + \pi^+$
	Σ^0	1192	1/2	0	$\overline{\Sigma}^0$	10^{-20}	$\Lambda^0 + \gamma$
	Σ^-	1197	1/2	−1	$\overline{\Sigma}^+$	1.7×10^{-10}	$n + \pi^-$
Xi†	Ξ^0	1315	1/2	0	$\overline{\Xi}^0$	3.0×10^{-10}	$\Lambda^0 + \pi^0$
	Ξ^-	1321	1/2	−1	$\overline{\Xi}^+$	1.7×10^{-10}	$\Lambda^0 + \pi^-$
Omega	Ω^-	1672	3/2	−1	Ω^+	1.3×10^{-10}	$\Xi^0 + \pi^-$
Charmed lambda	Λ_c^+	2285	1/2	+1	$\overline{\Lambda}_c^-$	1.8×10^{-13}	$p + K^- + \Lambda^+$
Mesons							
Pion	π^+	139.6	0	+1	π^-	2.6×10^{-8}	$\mu^+ + \nu_\mu$
	π^0	135	0	0	self	0.8×10^{-16}	$\gamma + \gamma$
	π^-	139.6	0	−1	π^+	2.6×10^{-8}	$\mu^- + \bar{\nu}_\mu$
Kaon	K^+	493.7	0	+1	K^-	1.24×10^{-8}	$\pi^+ + \pi^0$
	K^0	497.7	0	0	$\overline{K}^0$	0.88×10^{-10}	$\pi^+ + \pi^-$
						and	
						5.2×10^{-8}‡	$\pi^+ + e^- + \bar{\nu}_e$
Eta	η^0	549	0	0	self	2×10^{-19}	$\gamma + \gamma$

*Other decay modes also occur for most particles.
†The Ξ particle is sometimes called the cascade.
‡The K^0 has two distinct lifetimes, sometimes referred to as K^0_{short} and K^0_{long}. All other particles have a unique lifetime.

Table 12-11 Quark composition of selected hadrons

Baryons	Quarks	Mesons	Quarks
p	uud	π^+	$u\bar{d}$
n	udd	π^-	$\bar{u}d$
Λ^0	uds	K^+	$u\bar{s}$
Δ^{++}	uuu	K^0	$d\bar{s}$
Σ^+	uus	$\bar{K}^0$	$s\bar{d}$
Σ^0	uds	K^-	$s\bar{u}$
Σ^-	dds	J/ψ	$c\bar{c}$
Ξ^0	uss	D^+	$c\bar{d}$
Ξ^-	dss	D^0	$c\bar{u}$
Ω^-	sss	D_s^+	$c\bar{s}$
Λ_c^+	udc	B^+	$u\bar{b}$
Σ_c^{++}	uuc	$\bar{B}^0$	$\bar{d}b$
Σ_c^+	udc	B^0	$d\bar{b}$
Ξ_c^+	usc	B^-	$\bar{u}b$

Delta resonance states: Δ^-(ddd), Δ^0(udd), Δ^+(uud) and Δ^{++}(uuu)

Table 12-6 Some quantum numbers of the hadrons that are stable against decay via the strong interaction

Particle	Spin, $\hbar$	I	I_3	B	S	Y
p	1/2	1/2	+1/2	1	0	1
n	1/2	1/2	−1/2	1	0	1
Λ^0	1/2	0	0	1	−1	0
Σ^+	1/2	1	+1	1	−1	0
Σ^0	1/2	1	0	1	−1	0
Σ^-	1/2	1	−1	1	−1	0
Ξ^0	1/2	1/2	+1/2	1	−2	−1
Ξ^-	1/2	1/2	−1/2	1	−2	−1
Ω^-	3/2	0	0	1	−3	−2
π^+	0	1	+1	0	0	0
π^0	0	1	0	0	0	0
π^-	0	1	−1	0	0	0
K^+	0	1/2	+1/2	0	+1	+1
K^0	0	1/2	−1/2	0	+1	+1
η^0	0	0	0	0	0	0