Experimental Physics III – Test Exam

Time: 180 min

Important Note: Please write your name and your student number on every sheet **before** you start answering any problem. Please use a new page for each problem. Different questions on the front and back page of a sheet are okay. If given, please use the symbols used in the problem.

Exclusively for this Test Exam: The test exam will be discussed in the exercises. The tasks 4, 6, 7, and 11 will be corrected according to the same rules as for the exercises, i.e., one point at maximum for each of the stated tasks (and not with the points stated in the brackets that solely serve as an orientation and are only relevant for the exam). **Please submit your solutions for these tasks latest until January 19, 2023, before the lecture starts.**

1. Comprehension Questions (20 Points)

a) State Fermat's principle formally (including a small sketch) as well as in words. (**2 P**)

b) State under which condition total internal reflection occurs as well as an application example of this effect. Starting from Snell's law derive a formula for the critical angle for total internal reflection. (**2 P**)

c) Explain chromatic aberrations as an example of imaging errors. (**1 P**)

d) Explain what a wave is and state the relation between the wave's intensity I and its complex amplitude U. (**1 P**)

e) Consider the double-slit experiment: State a formula for the optical path difference Δs (i) resulting due to the experimental setup and (ii) for constructive interference to occur. Sketch the experimental setup and indicate the quantities that emerge in the formulas for Δs (as well as Δs itself). Furthermore, sketch the intensity pattern resulting from this experiment in dependence on $\sin(\theta)$ with θ the angle the rays make with the horizontal direction. (**4 P**)

f) Explain what the polarization of electromagnetic waves is. State two examples for a possible polarization of a wave as well as an example for its application. (**2 P**)

g) Shortly explain the difference between linear and nonlinear optics. (**1 P**)

h) Shortly explain the Drude model and state which property of metals this model (approximately) explains. State the respective equation of motion occurring in this model. (**2 P**)

i) Describe the main innovation of Rutherford's atom model in contrast to the plum pudding model. Explain the experiment which led Rutherford to this improvement. (**3 P**)

j) Shortly explain the main outcome of the Hallwachs experiment. (**1 P**)

k) Explain what the de Broglie wavelength of a particle is. (**1 P**)

2. Reflection and Refraction (4 Points)

A light ray in air hits a transparent material under an angle of 58° to the vertical. The reflected and the refracted rays are perpendicular to each other.

a) Calculate the index of refraction of the transparent material.

b) Calculate the critical angle for the total internal reflection.

3. Spherical Mirror (3 Points)

A spherical concave mirror of a telescope has a radius of curvature of 8.0 m. Using the paraxial limit calculate at which position the image of the moon is generated by this mirror as well as the diameter of the image. Assume that the moon has a diameter of $3.5 \cdot 10^6$ m and a distance of $3.8 \cdot 10^8$ m to the earth.

4. Thin Lenses (3 Points)

Using a thin bi-convex lens ($f = 10\,\text{cm}$) an image is generated that is twice as large as the small object.

a) Calculate the object distance as well as the image distance if the image is inverted.

b) Sketch the optical path of the system indicating the central ray, the parallel ray as well as the focal ray.

5. Newton Rings (6 Points)

A plane–convex lens with a radius of curvature of $R = 5$ m lays on a glass plate and is perpendicularly illuminated with a parallel light beam of a sodium lamp ($\lambda = 589.3$ nm) from above (Figure 1). The interstice is filled with water ($n = 1.34$). The refractive index of the lens and the glass plate is $n_\text{G} = 1.50$. The transmitted light exhibits Newton rings.

a) Calculate the optical path difference of the two beams shown in Figure 1.

b) State and shortly explain whether the position at which the lens and the plate touch each other appears bright or dark.

c) Derive a formula for the radius r of the Newton rings assuming $d \ll R$.

d) Calculate the maximum number of rings visible if the diameter of the lens is $D = 5$ cm.

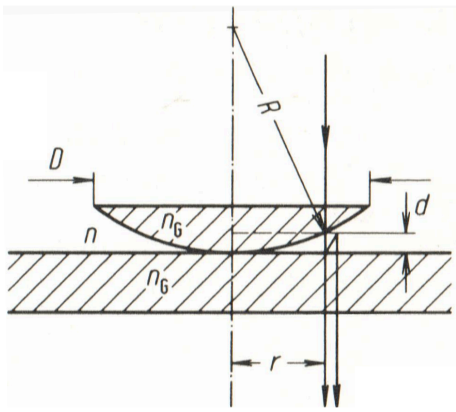


Figure 1: Newton rings due to a plane–convex lens laying on a glass plate.

6. Double-Slit Experiment (4 Points)

In a double-slit experiment a Fraunhofer interference and diffraction pattern is observed with light at a wavelength of 550 nm. Each of the two slits has a width of 0.03 mm and both are separated by a distance of 0.15 mm.

a) Calculate how many interference maxima occur in the total width of the central diffraction maximum.

b) Calculate the intensity of the third interference maximum with respect to the intensity of the central interference maximum. (Hint the central interference maximum counts as the zeroth interference maximum.)

7. Radiation Pressure (4 Points)

The LightSail spacecraft (Figure 2) has sails with a total area of $32\,\mathrm{m}^2$ as well as a total mass of $5\,\mathrm{kg}$.

a) Assuming an average power output of the sun of $3.8 \cdot 10^{26}$ W calculate the maximum radiation pressure on the sails if the LightSail spacecraft is 1 AU (astronomical unit), i.e., about $1.496 \cdot 10^{8}$ km, away from the sun.
Hints:

- At such large distances the sun can be approximated as a point source.
- Assume that the sails reflect all the incident light.

b) Calculate the maximum acceleration the LightSail spacecraft could achieve.

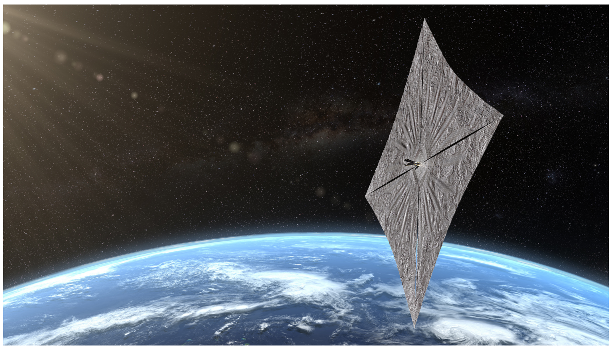


Figure 2: LightSail spacecraft accelerated via radiation pressure. Image taken from Wikipedia: "LightSail" (date of last retrieval: 04.01.2023).

8. Reflection of Linearly Polarized Light (6 Points)

Linearly polarized light (in air, $n_1 = 1$) hits a glass plate with a refractive index of $n_2 = 1.5$ at an incidence angle of θ_I. The oscillation plane of the electric vectors make an angle of $\phi = 45°$ with the plane of incidence.

a) Calculate the angle ϕ_r of the electric vector with the plane of incidence after reflection assuming $\theta_\mathrm{I} = 40°$.

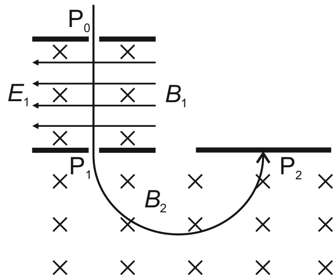
b) Calculate the percentage of the reflected intensity with respect to the incident intensity.

9. Specific Charge of Ions (3 Points)

Positively charged ions enter perpendicularly crossed fields at an electric field strength of $E_1 = 250$ V/m and a magnetic flux density of $B_1 = 10^{-3}$ T at the position P_0. One part of the ions straightly traverses the setup and passes an aperture P_1 into a magnetic field at a flux density $B_2 = 1$ T. The ions are deflected there and impinge on a screen at P_2 ($\overline{P_1 P_2} = 10$ cm).

a) Calculate the velocity of the ions, which straightly traverse the crossed fields and exit at P_1.

b) Calculate the specific charge q/m of the ions, which impinge on the screen at P_2.



10. Photoelectric Effect (2 Points)

Consider the photoelectric effect of a wolfram (tungsten) slab with a work function of $W_A = 4.6$ eV. The photocurrent vanishes at a counter-voltage of $U = 2.5$ V. Calculate the wavelength range of the incident photons.

11. Heat Radiation (5 Points)

A blackened, massive copper sphere with a radius of 4 cm hangs in an evacuated container the blackened walls of which have a temperature of 20.0 °C. The sphere has a temperature of 0.0 °C. Assume that the sphere as well as the walls behave as black bodies.

a) Calculate the wavelength of the maximal radiated power of the walls.

b) Calculate the rate at which the temperature of the sphere changes assuming that heat is solely transferred via radiation.
Hints:

- density of copper: $\rho_{Cu} = 8.93 \cdot 10^3$ kg/m^3
- specific heat capacity of copper: $c_{Cu} = 0.38$ kJ/(kg · K)

Constants

Elementary Charge:	$e \approx 1.602 \cdot 10^{-19}$ C
Electron Mass:	$m_e \approx 9.109 \cdot 10^{-31}$ kg
Proton Mass:	$m_p \approx 1.673 \cdot 10^{-27}$ kg
Neutron Mass:	$m_n \approx 1.675 \cdot 10^{-27}$ kg
Atomic Mass Unit:	$u \approx 1.661 \cdot 10^{-27}$ kg
Planck's Constant:	$h \approx 6.626 \cdot 10^{-34}$ J · s
Reduced Planck's Constant:	$\hbar = h/2\pi \approx 1.054 \cdot 10^{-34}$ J · s
Speed of Light:	$c \approx 2.998 \cdot 10^8$ m/s
Boltzmann Constant:	$k_B \approx 1.381 \cdot 10^{-23}$ J/K
Bohr Radius:	$a_0 \approx 0.529 \cdot 10^{-10}$ m
Rydberg Energy:	$R_y \approx 13.6$ eV
Stefan–Boltzmann constant:	$\sigma \approx 5.670 \cdot 10^{-8}$ W/(m^2 · K^4)
Compton Wavelength of the Electron:	$\lambda_C \approx 2.426 \cdot 10^{-12}$ m
Bohr Magneton:	$\mu_B \approx 9.274 \cdot 10^{-24}$ J/T
Nuclear Magneton:	$\mu_K \approx 5.051 \cdot 10^{-27}$ J/T
Vacuum Permittivity:	$\varepsilon_0 \approx 8.854 \cdot 10^{-12}$ A · s/(V · m)
Vacuum Permeability:	$\mu_0 \approx 4\pi \cdot 10^{-7}$ N/A^2