Physics 111

Exam #3

March 1, 2024

Name____________________________________

Please read and follow these instructions carefully:

- Read all problems carefully before attempting to solve them.
- Your work must be legible, and the organization clear.
- You must show all work, including correct vector notation.
- You will not receive full credit for correct answers without adequate explanations.
- You will not receive full credit if incorrect work or explanations are mixed in with correct work. Erase or cross out anything you don't want graded.
- Make explanations complete but brief. Do not write a lot of prose.
- Include diagrams.
- Show what goes into a calculation, not just the final number. For example, $|\vec{p}| \approx m|\vec{v}| = (5kg)\times\left(2\frac{m}{s}\right) = 10\frac{kg\cdot m}{s}$
- Give standard SI units with your results unless specifically asked for a certain unit.
- Unless specifically asked to derive a result, you may start with the formulas given on the formula sheet including equations corresponding to the fundamental concepts.
- Go for partial credit. If you cannot do some portion of a problem, invent a symbol and/or value for the quantity you can't calculate (explain that you are doing this), and use it to do the rest of the problem.
- Each free-response part is worth 6 points.

Problem #1	/24
Problem #2	/24
Problem #3	/24
Total	/72

I affirm that I have carried out my academic endeavors with full academic honesty.

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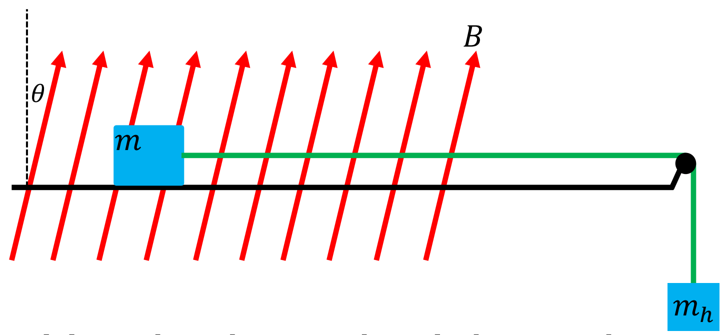
1. Consider the side-view of a circuit in which a bar of mass $m = 500g$, length $L = 10cm$ and resistance $R = 100\Omega$ slides across a set of frictionless U-shaped horizontal rails as shown below. The bar is attached by a massless string that passes over a massless pulley to a $m_h = 10g$ hanging mass and the masses are both released from rest. A uniform magnetic field of magnitude B points out through the loop and is oriented at $\theta = 10^0$ to the right of vertical.



a. When the bar slides to the right across the rails there is a change in magnetic flux through the loop defined by the location of the bar at any moment in time. Explain whether the magnetic flux is increasing or decreasing and what is the direction of the current flowing in the bar as viewed from the side shown in the figure. In other words, is the current flowing in the bar coming towards me out of the paper or into the paper away from me?

   As the bar slides down the rails to the right, the magnetic flux through the loop is increasing vertically. To undo the increase, the loop will generate a current and its own magnetic field that will point into the loop. To get magnetic field pointing vertically down, a clockwise current will be produced and will flow down the bar at me.

b. When the bar reaches a terminal speed $v = 1.5\frac{m}{s}$, what is the tension in the string?

$$F_T - F_{W_h} = m_h a_y = 0 \rightarrow F_T = F_{W_h} = m_h g = 0.010kg \times 9.8\frac{m}{s^2} = 0.098N$$

c. What is the magnitude of the constant external magnetic field B?

$$-F_{Bx} + F_T = -F_B \cos\theta + F_T = ma_x = 0 \rightarrow F_B \cos\theta = F_T$$

$$F_B \cos\theta = ILB\cos\theta = \frac{\varepsilon}{R} LB\cos\theta = \frac{(BLV\cos\theta)}{R} LB\cos\theta = \frac{B^2L^2v\cos^2\theta}{R} = F_T$$

$$B = \sqrt{\frac{RF_T}{L^2 v\cos^2\theta}} = \sqrt{\frac{100\Omega \times 0.098N}{(0.1m)^2 \times 1.5\frac{m}{s}\cos^2 10}} = 26T$$

d. What is the energy dissapated per second in the bar?

$$P = \frac{energy}{time} = I^2R = \left(\frac{\varepsilon}{R}\right)^2 R = \left(\frac{BLv\cos\theta}{R}\right)^2 R = \frac{B^2L^2v^2\cos^2\theta}{R}$$

$$P = \frac{(26T)^2(0.1m)^2\left(1.5\frac{m}{s}\right)^2\cos^2 10}{100\Omega} = 0.148W$$

2. A compound microscope containing two lenses is used to image *Heterocarpus ensifer* shrimp in a dish of water ($n_w = 1.33$). The objective lens (the lens closest to the shrimp in the dish) has a focal length $f_o = 15mm$ and is separated from the eyepiece by a distance $D = 45mm$. The image of the shrimp is projected through the eyepiece onto a screen $1.2m$ away. In the dish, the shrimp is located $10mm$ from the objective lens and its image on the screen is $150mm$ in height. Note: The photos in this problem are adapted from those of *Sönke Johnsen and Katie Thomas* located at: https://oceanexplorer.noaa.gov/explorations/15biolum/logs/july23/july23.html.

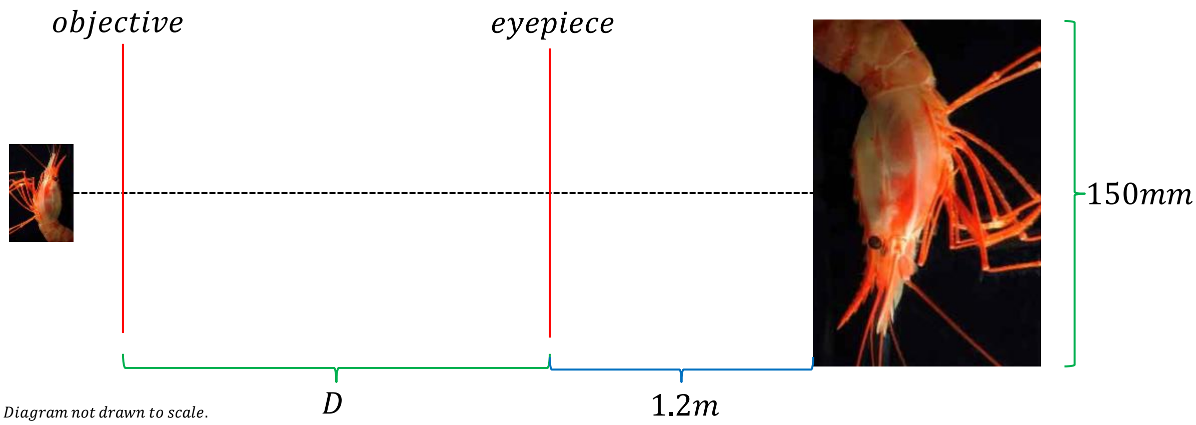


Diagram not drawn to scale.

a. What is the value of the focal length of the eyepiece, f_e?

$$\frac{1}{d_{oo}} + \frac{1}{d_{io}} = \frac{1}{f_o} \rightarrow \frac{1}{d_{io}} = \frac{1}{f_o} - \frac{1}{d_{oo}} = \frac{1}{15mm} - \frac{1}{10mm} \rightarrow d_{io} = -30mm$$

$$d_{oe} = D + d_{io} = 45mm + 30mm = 75mm$$

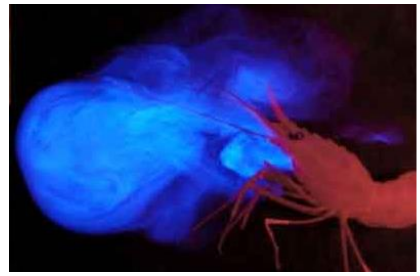
$$\frac{1}{f_e} = \frac{1}{d_{oe}} + \frac{1}{d_{ie}} = \frac{1}{75mm} + \frac{1}{1200mm} \rightarrow f_e = 70.6mm$$

b. How big is the shrimp in the dish?

$$M_{total} = M_o M_e = \frac{h_{if}}{h_o} \rightarrow h_o = \frac{h_{if}}{M_o M_e} = \frac{h_{if}}{\frac{d_{io}}{d_{oo}} \times \frac{d_i e}{d_{oe}}}$$

$$h_o = \frac{150mm}{\frac{30mm}{10mm} \times \frac{1200m}{75mm}} = \frac{150mm}{48} = 3.1mm$$

c. In the image on the right of the shrimp on the screen, the shrimp appears to emit some bioluminescent fluid (the blue liquid) against a black background. The blue light has a wavelength of $\lambda = 300nm$ in the water with an intensity of $130\frac{W}{m^2}$. What is the frequency of the emitted light and the maximum values of the electric and magnetic fields in the light?



$$v = \frac{c}{n} = f\lambda \rightarrow f = \frac{c}{n_w\lambda} = \frac{3\times10^8\frac{m}{s}}{1.33\times300\times10^{-9}m} = 7.5\times10^{14}s^{-1}$$

$$S = \frac{1}{2}c\varepsilon_0E_{max}^2 \rightarrow E_{max} = \sqrt{\frac{2S}{c\varepsilon_0}} = \sqrt{\frac{2\times130\frac{W}{m^2}}{3\times10^8\frac{m}{s}\times8.85\times10^{-12}\frac{C^2}{Nm^2}}} = 312.9\frac{N}{C}$$

$$E_{max} = cB_{max} \rightarrow B_{max} = \frac{E_{max}}{c} = \frac{312.9\frac{N}{C}}{3\times10^8\frac{m}{s}} = 1.0\times10^{-6}T$$

Or $S = \frac{c}{2\mu_0}B_{max}^2 \rightarrow B_{max} = \sqrt{\frac{2\mu_0S}{c}} = \sqrt{\frac{2\times4\pi\times10^{-7}\frac{Tm}{A}\times130\frac{W}{m^2}}{3\times10^8\frac{m}{s}}} = 1.0\times10^{-6}T$

d. Explain how you could tell if the bioluminescent light emitted were polarized or not and if it is polarized, the direction of polarization. To earn full credit be sure to fully explain your answer.

By placing a polarizer in front of the observer and the emitted blue light and rotating the polarizer will tell you if the light is polarized or not. As the polarizer is rotated, if the light is polarized there should be an orientation of the polarizer in which the light vanishes. In this orientation the electric field from the blue light and the transmission axis of the polarizer would be crossed and thus no light comes out. This would tell you both whether the light was polarized and in what direction. On the other hand, as the polarizer is rotated, if the light does not vanish, then the light must have been unpolarized.

3. Tungsten x-rays are used in a Compton effect experiment. The incident tungsten x-rays have an energy $59.3182keV$ and are observed to scatter from stationary electrons at an angle ϕ measured counterclockwise with respect to the incident direction of the x-ray beam, taken to be long the horizontal at an angle of 0^0.

   a. If the electrons were known to scatter at an angle $\theta = 31.5$ below the horizontal with a speed $v = 0.176c$, what was the energy of the scattered x-rays?

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(0.176c)^2}{c^2}}} = 1.01586$$

$$E' = E - K = E - (\gamma - 1)mc^2 = 59.3182keV - (0.01586) \times 511\frac{keV}{c^2}c^2$$

$$E' = 51.2137keV$$

   b. At what angle ϕ was the x-ray detector placed?

$$\frac{1}{E'} = \frac{1}{E} + \frac{1-\cos\phi}{mc^2} \rightarrow \cos\phi = 1 - \left(\frac{1}{E'} - \frac{1}{E}\right)mc^2$$

$$\cos\phi = 1 - \left(\frac{1}{51.2137keV} - \frac{1}{59.3182keV}\right) \times 511\frac{keV}{c^2} \times c^2 = -0.3632$$

$$\phi = \cos^{-1}(-0.3632) = 111.3^0$$

c. Suppose instead of using the tungsten x-rays in a Compton effect experiment, the x-rays were used in a photoelectric effect experiment where the x-rays are incident on electrons in a lead ($\phi = 4.14eV$) target with an intensity $S = 1.2\frac{mW}{m^2}$. How many photons per second are incident on the lead target if the beam on the lead target makes a spot $2mm$ in diameter?

$$S = \frac{Energy}{time \cdot area} = \frac{N \cdot E_{photon}}{time \cdot area} \rightarrow \frac{N}{time} = \frac{S \cdot area}{E_{photon}}$$

$$\frac{N}{time} = \frac{\left[1.2 \times 10^{-3}\frac{W}{m^2} \times \pi(1 \times 10^{-3}m)^2\right] \times \frac{1eV}{1.6 \times 10^{-19}J}}{59318.2eV} = 4 \times 10^5 \frac{photos}{s}$$

d. Are electrons ejected from the lead target by the tungsten x-rays? To earn full credit, you must show a calculation or explain your answer in full unambiguous detail?

For electrons to be ejected from the lead surface, the kinetic energy of the ejected electron must be greater than or equal to zero. The kinetic energy of the electron is the difference between the incident photon's energy and the binding energy of the electron in lead. Since the energy of the incident photons is so much greater than the binding energy of electrons in lead, electrons will be ejected.

Or $K = E_{ph} - \phi = 59318.2eV - 4.14eV = 59314eV$ and this is positive, electrons are ejected.

Physics 111 Formula Sheet

Electrostatics

$F = k\frac{q_1 q_2}{r^2}$

$\vec{F} = q\vec{E}; \quad E_{pc} = k\frac{q}{r^2}; \quad E_{plate} = \frac{q}{\epsilon_0 A}$

$E = -\frac{\Delta V}{\Delta x}$

$V_{pc} = k\frac{q}{r}$

$U_e = k\frac{q_1 q_2}{r} = qV$

$W = -q\Delta V = -\Delta U_e = \Delta K$

Magnetism

$\vec{F} = q\vec{v} \times \vec{B} \rightarrow F = qvB\sin\theta$

$\vec{F} = I\vec{L} \times \vec{B} \rightarrow F = ILB\sin\theta$

$V_{Hall} = wv_d B$

$B = \frac{\mu_0 I}{2\pi r}$

$\varepsilon = \Delta V = -N\frac{\Delta\phi_B}{\Delta t}$

$\phi_B = BA\cos\theta$

Electric Circuits - Capacitors

$Q = CV; \quad C = \frac{\kappa\epsilon_0 A}{d}$

$C_{parallel} = \sum_{i=1}^{N} C_i$

$\frac{1}{C_{series}} = \sum_{i=1}^{N}\frac{1}{C_i}$

$Q_{charging}(t) = Q_{max}\left(1 - e^{-\frac{t}{\tau}}\right)$

$Q_{discharging}(t) = Q_{max}e^{-\frac{t}{\tau}}$

$I(t) = I_{max}e^{-\frac{t}{\tau}} = \frac{Q_{max}}{\tau}e^{-\frac{t}{\tau}}$

$\tau = RC$

$U_C = \frac{1}{2}qV = \frac{1}{2}CV^2 = \frac{Q^2}{2C}$

Electric Circuits - Resistors

$I = \frac{\Delta Q}{\Delta t}$

$I = neAv_d; \quad n = \frac{\rho N_A}{m}$

$V = IR$

$R = \frac{\rho L}{A}$

$R_{series} = \sum_{i=1}^{N} R_i$

$\frac{1}{R_{parallel}} = \sum_{i=1}^{N}\frac{1}{R_i}$

$P = \frac{\Delta E}{\Delta t} = IV = I^2 R = \frac{V^2}{R}$

Light as a Wave

$c = f\lambda$

$S(t) = \frac{\text{Energy}}{\text{time}\times\text{Area}} = c\epsilon_0 E^2(t) = c\frac{B^2(t)}{\mu_0}$

$I = S_{avg} = \frac{1}{2}c\epsilon_0 E_{max}^2 = c\frac{B_{max}^2}{2\mu_0}$

$P = \begin{cases} \frac{S}{c}; & \text{absorbed} \\ \frac{2S}{c}; & \text{reflected} \end{cases}$

$S = S_0\cos^2\theta$

$v = \frac{c}{n}$

$\theta_{\text{incident}} = \theta_{\text{reflected}}$

$n_1\sin\theta_1 = n_2\sin\theta_2$

$P = \frac{1}{f} = \frac{1}{d_0} + \frac{1}{d_i}$

$M = \frac{d_i}{d_0}; \quad |M| = \frac{h_i}{h_0}$

Light as a Particle/Relativity

$E = hf = \frac{hc}{\lambda}$

$K_{max} = hf - \phi$

$\Delta\lambda = \lambda' - \lambda = \frac{h}{mc}(1 - \cos\phi)$

$\frac{1}{E'} = \frac{1}{E} + \frac{(1-\cos\phi)}{E_{rest}}; \quad E_{rest} = mc^2$

$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$p = \gamma mv$

$E_{total} = E_{rest} + K = \gamma mc^2$

$K = (\gamma - 1)mc^2$

$E_{total}^2 = p^2c^2 + m^2c^4$

Nuclear Physics

$N = N_0 e^{-\lambda t}$

$m = m_0 e^{-\lambda t}$

$A = A_0 e^{-\lambda t}$

$A = \lambda N$

$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Constants

$g = 9.8 \frac{m}{s^2}$

$1e = 1.6 \times 10^{-19} C$

$k = \frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \frac{Nm^2}{C^2}$

$\epsilon_0 = 8.85 \times 10^{-12} \frac{C^2}{Nm^2}$

$1eV = 1.6 \times 10^{-19} J$

$\mu_0 = 4\pi \times 10^{-7} \frac{Tm}{A}$

$c = 3 \times 10^8 \frac{m}{s}$

$h = 6.63 \times 10^{-34} Js = 4.14 \times 10^{-15} eVs$

$N_A = 6.02 \times 10^{23}$

$1u = 1.66 \times 10^{-27} kg = 931.5 \frac{MeV}{c^2}$

$m_p = 1.67 \times 10^{-27} kg = 937.1 \frac{MeV}{c^2}$

$m_n = 1.69 \times 10^{-27} kg = 948.3 \frac{MeV}{c^2}$

$m_e = 9.11 \times 10^{-31} kg = 0.511 \frac{MeV}{c^2}$

Physics 110 Formulas

$\vec{F} = m\vec{a}; \quad F_G = \frac{GM_1 m_2}{r^2}; \quad F_s = -ky; \quad a_c = \frac{v^2}{r}$

$W = -\Delta U_g - \Delta U_s = \Delta K$

$U_g = mgy$

$U_s = \frac{1}{2} k y^2$

$K = \frac{1}{2} m v^2$

$\vec{r}_f = \vec{r}_i + \vec{v}_i t + \frac{1}{2}\vec{a} t^2$

$\vec{v}_f = \vec{v}_i + \vec{a} t$

$v_f^2 = v_i^2 + 2a_r \Delta r$

Common Metric Units

$nano\ (n) = 10^{-9}$

$micro\ (\mu) = 10^{-6}$

$milli\ (m) = 10^{-3}$

$centi\ (c) = 10^{-2}$

$kilo\ (k) = 10^{3}$

$mega\ (M) = 10^{6}$

Geometry/Algebra

Circles: $A = \pi r^2$ $\quad C = 2\pi r = \pi$

Spheres: $A = 4\pi r^2$ $\quad V = \frac{4}{3}\pi r^3$

Triangles: $A = \frac{1}{2} bh$

Quadratics: $ax^2 + bx + c = 0 \rightarrow x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$