

Constants you may find useful

$$G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$$

$$M_{\text{Earth}} = 5.97 \times 10^{24} \text{ kg}$$

$$M_{\text{Sun}} = 1.99 \times 10^{30} \text{ kg}$$

$$r_{\text{Earth}} = 6.38 \times 10^3 \text{ km}$$

$$r_{\text{Sun}} = 6.96 \times 10^5 \text{ km}$$

$$d_{\text{Sun-Earth}} = 149.6 \times 10^6 \text{ km}$$

$$g = 9.8 \text{ m/s}^2$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/(\text{Nm}^2)$$

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

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

$$h = 6.626 \times 10^{-34} \text{ Jsec}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$m_p = 1.6726 \times 10^{-27} \text{ kg}$$

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

Part I. [37 Points] In the Bohr model for the hydrogen atom, the distance between the electron and the proton in the ground state is one Bohr radius, 0.0529 nm.

1. [5 pts] Find the force on the proton in Newton's when the atom is in the ground state.

- A. 1.0×10^{-27} N
 B. 4.4×10^{-18} N
 C. 8.2×10^{-8} N
 D. 1.0×10^{-6} N
 E. 5.1×10^{11} N

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} = 9 \times 10^9 \frac{(1.6 \times 10^{-19})^2}{(0.0529 \times 10^{-9})^2}$$

$$= 8.233 \times 10^{-8} \text{ N}$$

2. [4 pts] SI units are often not convenient for atomic problems. Find the force in number 1 in units appropriate to atomic physics, eV/nm.

- A. 6.4×10^{-18} eV/nm
 B. 2.7×10^{-8} eV/nm
 C. 5.1×10^2 eV/nm
 D. 6.5×10^3 eV/nm
 E. 3.2×10^{21} eV/nm

$$F = (F) \frac{1}{1.6 \times 10^{-19}} \cdot 1 \times 10^{-9}$$

$$= 514. \text{ eV/nm}$$

3. [5 pts] Find the magnitude of the momentum of the electron in the hydrogen atom ground state in SI units.

- A. 1.5×10^{-29} kgm/s
 B. 2.0×10^{-24} kgm/s
 C. 7.1×10^{-24} kgm/s
 D. 4.4×10^{-18} kgm/s
 E. 5.0×10^{-15} kgm/s

$$F = \frac{mv^2}{r} \Rightarrow v = \sqrt{\frac{rF}{m}}$$

$$p = mv = \sqrt{rmF} = \sqrt{(0.0529 \times 10^{-9}) (9.11 \times 10^{-31}) (8.23 \times 10^{-8})}$$

4. [4 pts] The unit for momentum in units appropriate to atomic physics is eV/c, i.e. eV (the unit for energy) divided by the speed of light. Find the momentum of part 3 in units of eV/c.

- A. 2.7×10^{-2} eV/c
 B. 3.7×10^3 eV/c
 C. 1.3×10^4 eV/c
 D. 8.2×10^9 eV/c
 E. 9.3×10^{12} eV/c

$$p = p \cdot \frac{3 \times 10^8}{1.6 \times 10^{-19}}$$

$$= 3712.5 \text{ eV/c}$$

$$= 1.98 \times 10^{-24} \text{ kg m/s}$$

5. [5 pts] The H atom in its ground state is excited to what state by the absorption of a photon with wavelength 103 nm (infrared)?

- A. N=1
 B. N=2
 C. N=3
 D. N=4
 E. N=5

know ground state is $-13.6 \text{ eV} = E_1$

$$\hookrightarrow E_n = \frac{Z^2}{n^2} E_1$$

$$\Delta E = E_1 - E_n = hf$$

$$\Delta E = hf = (h) \frac{v}{\lambda}$$

$$= \frac{(6.626 \times 10^{-34}) (3 \times 10^8)}{103 \times 10^{-9}}$$

$$\lambda = vT$$

$$= \frac{v}{f}$$

$$f = \frac{v}{\lambda}$$

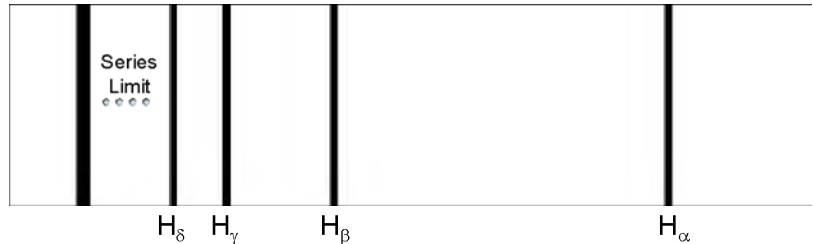
$$= 12.061 \text{ eV}$$

$$\text{so } E_n = 1.53 \text{ eV}, n^2 = \frac{E_1}{E_n} \Rightarrow n = 2.97$$

This is UV, not infrared (this does not affect the problem, however)

Well. I hate rounding. An equally valid answer for this problem is that since it doesn't hit the N=3 energy exactly, it will not be absorbed at all. I'll give credit for either A or C.

Consider the **emission** spectra at right for the H atom.



6. [5 pts] What is the energy change of the atom when it emits light for the line H_γ ?

A. 1.8×10^{-21} eV
 B. 5.4×10^{-13} eV
☒ C. 2.9 eV
 D. 3.7 eV
 E. Not enough information

$H_\alpha: \lambda = 656$ nm

$H_\gamma: \lambda = 434$ nm

$H_\beta: \lambda = 486$ nm

$H_\delta: \lambda = 397$ nm

$$E = hf = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \text{ J}\cdot\text{s} \times 3 \times 10^8 \text{ m/s}}{434 \times 10^{-9} \text{ m}} = 2.86 \text{ eV}$$

7. [4 pts] Which of the following statements is correct?

A. The emission lines are generated by absorption by the atom of the photon of that wave length.
☒ B. The emission lines are generated when the atom drops from an excited state to a state closer to the ground state.
 C. The emission lines match the wave length of the electron orbiting the nucleus.
 D. Each emission line represents a wave length that corresponds to the energy state of an atom (E_1 , E_2 , etc.).
 E. Either A or D.

8. [5 pts] Which of the following statements is correct when comparing the He^+ (2 protons, one electron) and the H atom (1 proton):

☒ A. The ground state classical radius of the atom will be smaller for the He^+ atom.
 B. The ground state classical velocity of the He^+ will be the same as that of the H atom.
 C. Instead of quantizing angular momentum in terms of $nh/2\pi$, it will be in terms of nh/π .
 D. The frequency of the photons radiated while the atom is in the ground state will be higher for the He^+ atom.
 E. There isn't enough information to tell.

Part II. [21 Points] The siren of a police car emits a pure tone of 1010 Hz. The speed of sound is 343 m/s.

9. [5 Points] What frequency would you hear in your car if it was at rest and the police car was moving toward you at 15 m/s?

A. 15.7 Hz

B. 966 Hz

C. 968 Hz

D. 1010 Hz

☒ E. 1060 Hz

$$f = f \left(\frac{v + v_o}{v - v_s} \right) = f \left(\frac{v}{v - v_s} \right)$$

$$= 1010 \left(\frac{343}{343 - 15} \right)$$

$$= 1056.1 \text{ Hz}$$

10. [5 Points] What frequency would you hear in your car if the police car was at rest and you were moving toward the police car at 15 m/s?

Away from the cop car!
 (as written on the board during the exam). The correct answer is B.

A. 15.7 Hz

B. 966 Hz

C. 968 Hz

D. 1010 Hz

☒ E. 1050 Hz

$$f = f \left(\frac{v + v_o}{v - v_s} \right) = f \left(\frac{v + v_o}{v} \right) = 1010 \left(\frac{343 + 15}{343} \right)$$

$$= 1054.1 \text{ Hz}$$

11. [5 Points] If you and the police car were moving towards each other with a relative speed of 32 m/s, what frequency would you hear in your car?

A. 1500 Hz

B. 1110 Hz

C. 1240 Hz

D. 1250 Hz

☒ E. Not Enough Information to Tell

What are the relative speeds??

12. [6 Points] What frequency would you hear in your car if you were moving at 9 m/s and the police car was chasing you at 38 m/s?

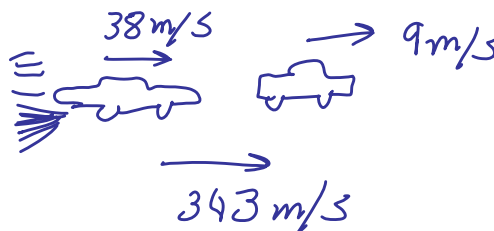
A. 925 Hz

B. 1070 Hz

C. 1100 Hz

☒ D. 1110 Hz

E. 1210 Hz



2 steps

1) f_a - f in air for stationary person

$$f_a = f \left(\frac{v}{v - v_{pol}} \right)$$

2) f_y - what you hear. You are moving away from source.

$$f_y = f_a \left(\frac{v - v_{car}}{v} \right)$$

$$= f \left(\frac{v}{v - v_{pol}} \right) \left(\frac{v - v_{car}}{v} \right) = f \left(\frac{v - v_{car}}{v - v_{pol}} \right)$$

$$= 1106.03 \text{ Hz}$$

Part III. [22 points] A transmission diffraction grating has a 2000 slits/cm, and is illuminated by a light with $\lambda = 550$ nm. A very large screen is placed 2 meters from the diffraction grating.

13. [4 pts] The sizes of the slits are halved, but the spacing between them is kept the same. The angle of the second principle maxima:

A. Increases
 B. Decreases
 C. Remains the Same.
 D. Not enough information.

It just gets brighter

14. [4 pts] All but the two center slits of the original grating are blocked off. The angle of the second principle maxima:

A. Increases
 B. Decreases
 C. Remains the same.
 D. Not enough information.

*2 slit interf: $d \sin \theta = n\lambda$
 grating: $d \sin \theta = n\lambda$*

15. [5 pts] What is the relative phase difference between the light that comes from the upper and lower slit when one looks at a point on the screen 6 degrees below the horizontal (see figure)?

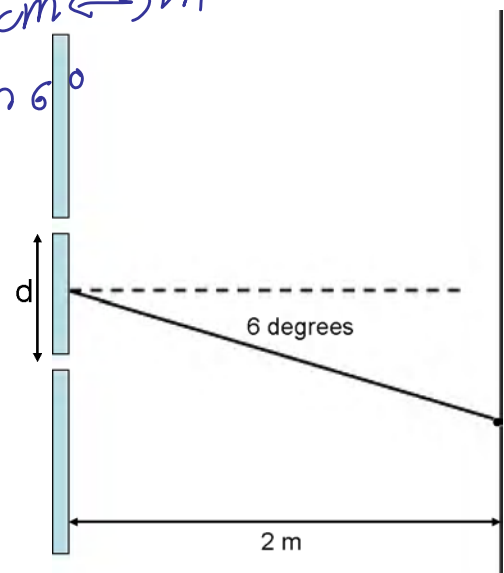
A. 0.95 radians
 B. 6.0 radians
 C. 7.1 radians
 D. 16 radians
 E. 600 radians

*$d \sin \theta = \frac{1}{2000} \cdot \frac{1}{100} \cdot \sin 6^\circ$
 $= 5.22 \times 10^{-7}$
 $\phi = \frac{d \sin \theta}{\lambda} \cdot 2\pi = 5.970$*

16. [5 pts] Destructive interference will occur when the path difference between the two light rays is (watch significant figures):

A. 140 nm
 B. 180 nm
 C. 280 nm
 D. 550 nm
 E. 1100 nm

$\frac{550}{2} = 275 \text{ nm}$



17. [4 pts] How intensity of light is related to amplitude of a light wave?

A. The intensity is proportional to the amplitude.
 B. The intensity is proportional to twice the amplitude.
 C. The intensity is proportional to the square root of the amplitude.
 D. The intensity is proportional to the square of the amplitude.
 E. The intensity is proportional to the cube of the amplitude.

A different electromagnetic plane wave is shown at right. A bulb connected to a thin conducting wire is placed in the wave with the wire parallel to the y -axis. In Case Q, the bulb is centered on the x -axis. In Case R, the bulb is shifted in the y -direction from Case Q, such that the lower end of the wire is on the x -axis. In Case S, the bulb is shifted in the z -direction from Case Q.

21. [4 pts] The bulb is initially positioned as shown in Case Q. The bulb is then moved to the position shown in Case R. Does the apparent brightness of the bulb *increase*, *decrease*, or *remain the same*?

A. The brightness *increases*.
 B. The brightness *decreases*.
 C. The brightness *remains the same*.
 D. It is not possible to determine from the information given.

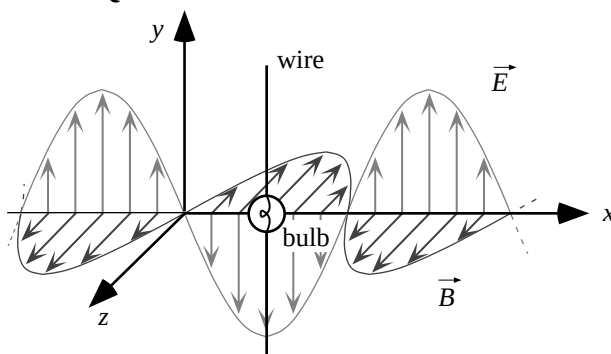
This is a plane wave propagating in the $+x$ direction, so the values of E and B are the same everywhere with the same x value. The bulb has the same x value and is parallel to E in both cases, so the current through the bulb will be the same, and it will appear equally bright.

22. [4 pts] The bulb is initially positioned as shown in Case Q. The bulb is then moved to the position shown in Case S. Does the apparent brightness of the bulb *increase*, *decrease*, or *remain the same*?

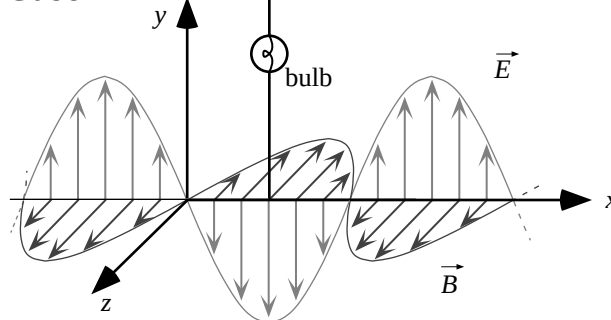
A. The brightness *increases*.
 B. The brightness *decreases*.
 C. The brightness *remains the same*.
 D. It is not possible to determine from the information given.

Same reasoning as previous question.

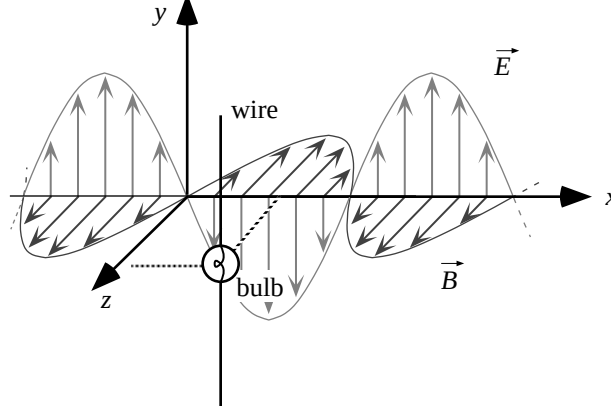
Case Q



Case R

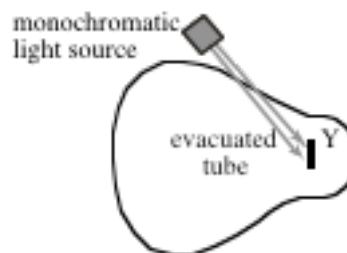


Case S



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last first

Electrode Z is now removed from the tube, and the circuit is disconnected from electrode Y. Electrode Y is illuminated with monochromatic light of the same frequency and intensity as in the original experiment.



26. [2 pts] Will any electrons be emitted from electrode Y?

Yes, just as they were in problem 24.

27. [5 pts] If the intensity of the light is increased, will the number of electrons emitted *increase, decrease, or remain the same*? Explain. If no electrons are emitted, state so explicitly.

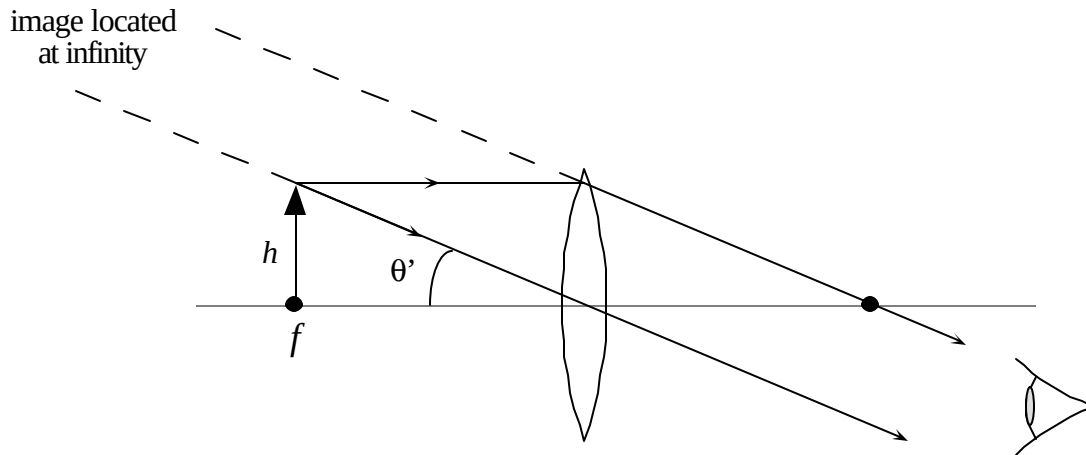
If the intensity of the light is increased, more electrons will be ejected, but they will not get any more energy. Increasing the intensity corresponds to increasing the number of incident photons and thus the number of ejected electrons.

Part VI. [25 Points] Optics

28. [4 pts] A microbe (a very small life form) has a spherical shape, with diameter 10 mm . If it is viewed by eye, from a distance of 25 cm , what is its angular width? Show your work.

If the near point is at 25 cm , the angle subtended is $10 \times 10^{-6} / 0.25\text{ radians}$, or $\text{angle} = 0.0023\text{ degrees}$

29. [7 pts] Design a simple magnifier, using a single converging lens, so that the angular width of the microbe appears to be 0.02 degrees when its image is at infinity. On the provided optic axis, neatly draw the lens and two principal rays, and show the object location with respect to the focal points. Exaggerate the angles for clarity!



Drawing should show converging lens [1pt] with object at focal point [2 pts], 2 principal rays [2 pts], parallel extended back to infinity dotted [1 pt], clarity [2pt].

30. [3 pts] Show how to calculate the angular width of the image by geometry, and express the focal length in terms of given quantities. You may use the small angle approximation if appropriate.

Angular size = $\tan^{-1} h/f \approx h/f$

Angular magnification = $0.02\text{ degree} / 0.0023\text{ degree}$ [2pts]. Image and object both upright, so sign is +. [1 pt]

31. [4
pts]
Wh
at is

the angular magnification (sign and magnitude)? Show your work.

32. [7 pts] If the space between the microbe and the first surface of the lens were to be filled with water, what adjustment to the position of the lens would have to be made relative to the microbe to keep the image at infinity? Qualitative, not numerical, answers are expected. Be sure to give your reasoning. Assume both surfaces of the lens are convex.

The addition of water, which has a refractive index of 1.33 instead of 1 , means the bending of rays at the first surface is reduced and the focal length increases. Hence the magnification decreases, because the magnification of a simple magnifier is $25/f$. (The

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first

angle subtended without the magnifier is $h/25$, and with the magnifier is h/f , when angles are small). One can also consider the water to form a single-surface concave lens with the concave surface nested with the convex surface of the glass lens. The combined focal length of a converging and diverging lens is always longer than the converging lens' (specifically, $1/f_{\text{total}} = 1/f_{\text{conv}} + 1/f_{\text{div}}$, and since f_{div} is negative, the effect is to make f_{total} larger than f_{conv}).

All that is expected here is

Water has a refractive index larger than 1 [2pts]

This makes the refraction less at the first surface [2 pts]

This makes the focal length of the lens greater [3 pts]