Last Name:________________________First Name__________________ID____________________
Discussion Section:___________Discussion TA Name:_____________________________________
Exam Room & Building _______________________ Seat Number____________

Instructions— ***Turn off your cell phone and put it away.***

This is a closed book exam. You have two (2) hours to complete it.

I. Fill in ALL the information requested on the lines above and sign the Formula Sheet.

II. At the end of this exam, you ***must*** return this Exam Booklet complete with all pages, including the formula sheet, along with your answer sheet. Note that this is a different policy than the one applying to midterm exams.

III. If you do not turn in a complete Exam Booklet, including the formula sheet, your Answer Sheet will not be graded and you will receive the grade AB (Absent) for this exam. Kindly paper clip the Answer Sheet to the Exam Booklet

1. Use a #2 pencil; do **not** use a mechanical pencil or a pen. Fill in completely (until there is no white space visible) the circle for each intended input – both on the identification side of your answer sheet and on the side on which you mark your answers. If you decide to change an answer, erase vigorously; the scanner sometimes registers incompletely erased marks as intended answers; this can adversely affect your grade. Light marks or marks extending outside the circle may be read improperly by the scanner.

2. Print your last name in the **YOUR LAST NAME** boxes on your answer sheet and print the first letter of your first name in the **FIRST NAME INI** box. Mark (as described above) the corresponding circle below each of these letters.

3. Print your NetID in the **NETWORK ID** boxes, and then mark the corresponding circle below each of the letters or numerals. Note that there are different circles for the letter “I” and the numeral “1” and for the letter “O” and the numeral “0”. **Do not** mark the hyphen circle at the bottom of any of these columns.

4. **This Exam Booklet is Version A**. Mark the **A** circle in the **TEST FORM** box at the bottom of the front side of your answer sheet.

5. Stop **now** and double-check that you have bubbled-in all the information requested in 2 through 4 above and that your marks meet the criteria in 1 above. Check that you do not have more than one circle marked in any of the columns.

6. Do **not** write in or mark any of the circles in the STUDENT NUMBER or SECTION boxes.

7. On the **SECTION** *line*, print your **DISCUSSION SECTION**. (You need not fill in the COURSE or INSTRUCTOR lines.)

8. Sign **(DO NOT PRINT)** your name on the **STUDENT SIGNATURE** *line*.

CHECK NOW THAT YOU HAVE COMPLETED ALL THE ABOVE STEPS. YOUR GRADE DEPENDS ON IT!

Before starting work, check to make sure that your test booklet is complete. You should have 15 pages (36 problems), excluding the Formula Sheets at the end. Grading policy is explained on page 2.

Academic Integrity—Giving assistance to or receiving assistance from another student or using unauthorized materials during a University Examination can be grounds for disciplinary action, up to and including dismissal from the university.

Exam Grading Policy—

The exam is worth a total of ___ points; it is composed of two types of questions.

MC5: multiple-choice-five-answer questions, each worth 6 points.
Partial credit will be granted as follows.

(a) If you mark only one answer and it is the correct answer,
you earn 6 points.
(b) If you mark two answers, one of which is the correct answer,
you earn 3 points.
(c) If you mark three answers, one of which is the correct answer,
you earn 2 points.
(d) If you mark no answers, or more than three, you earn 0 points.

MC3: multiple-choice-three-answer questions, each worth 3 points.
No partial credit.

(a) If you mark only one answer and it is the correct answer,
you earn 3 points.
(b) If you mark a wrong answer or no answers, you earn 0 points.

1. A beam of photons with wavelength 150 nm and beam of electrons having the same energy as the photons go through the same slit of width 355 nm. You observe the diffraction pattern on a distant screen. All angles are measured from the centerline. The ***photons*** produce their first dark band at an angle α. Is the magnitude of α bigger than, equal to, or smaller than the magnitude the angle, β, where the ***electrons*** produce their first dark band?

a. $|\alpha| > |\beta|$
b. $|\alpha| = |\beta|$
c. $|\alpha| < |\beta|$

2. It takes 3.0 eV of energy to excite an electron in a 1-dimensional infinite well from the ground state to the first excited state. What is the width, *L,* of the box?

a. $L = 0.25$ nm
b. $L = 0.61$ nm
c. $L = 2.10$ nm
d. $L = 10.6$ nm
e. $L = 109$ nm

The next two questions are related to the following situation:

A particle of unknown mass is in a 1-dimensional box of width $L = 3.0 \times 10^{-10}$ m with infinitely high potential walls at $x = 0$ and at $x = L$, and zero potential for $0 < x < L$. The particle is in the ***second excited state*** of the box.

3. What is the de Broglie wavelength, λ, of the particle?

a. $\lambda = 1.0 \times 10^{-10}$ m
b. $\lambda = 2.0 \times 10^{-10}$ m
c. $\lambda = 3.0 \times 10^{-10}$ m
d. $\lambda = 6.0 \times 10^{-10}$ m
e. Not enough information is given.

4. For which values of x is the ***probability*** of finding the particle largest?

a. Only at $x = L/6$ and $x = 5\,L/6$ (two values of x)
b. Only at $x = L/4$ (one value of x)
c. Only at $x = L/6$ and at $x = L/2$ and at $x = 5L/6$ (three values of x)
d. The probability is everywhere the same.
e. Not enough information is given.

The next two questions are related:

5. How many distinct (n,l,m) states of the hydrogen atom with n = 3 are there? Neglect electron spin.

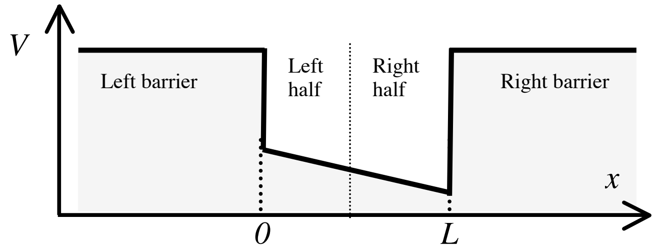
a. 1 distinct state
b. 5 distinct states
c. 9 distinct states

6. Which statement about the energies of the (n,l,m) states of the hydrogen atom with n = 3 is correct?

a. They are all equal to -1.51 eV.
b. The highest (most positive) energy is equal to -1.51 eV, the others are all smaller.
c. At least one energy is equal to -2.44 eV.
d. At least one energy is equal to +3.55 eV.
e. States with larger l have higher energies.

The next two questions pertain to the following situation:

A particle is in a bound energy state of the finite depth potential well shown.



7. If we measure the particle's position in the well, which is the more likely result?

a. The particle is more likely to be found in the left half of the well.
b. The particle is more likely to be found in the right half of the well.
c. The particle is equally likely to be found near both barriers.

8. At which values of x is the **total** energy of the particle the largest?

a. At $x = 0$
b. At $x = L$
c. The energy is the same everywhere.

9. The longest wavelength of light that can be absorbed by a particular harmonic oscillator is $\lambda = 1000$ nm. What is the second longest wavelength that can be absorbed?

a. $\lambda = 188$ nm
b. $\lambda = 300$ nm
c. $\lambda = 500$ nm
d. Every $\lambda \leq 1000$ nm can be absorbed.
e. No shorter wavelengths can be absorbed.

10. Consider a well that has an adjustable shape, so that we can vary its two lowest energy levels, E_1 (the ground state) and E_2. We will put a particle into a superposition of the two energy states (*i.e.*, $\Psi = a\psi_1 + b\psi_2$). Which of these manipulations will increase the frequency of oscillation of the particle's spatial probability density?

a. Increase E_1, keeping E_2 constant.
b. Increase $|E_2 - E_1|$.
c. Increase a, keeping b constant.
d. Increase $|b - a|$.
e. None of the above.

The next three questions pertain to the following situation:

An electron is confined to an infinite 1-dimensional well of width $L = 1.5$ nm. At $t = 0$, it is in a superposition of the ground state and **<u>second</u>** excited state: $\Psi(x, t=0) = a\psi_1 + b\psi_3$.

11. What is the frequency of oscillation, f, of the spatial probability density?

a. $f = 1.27 \times 10^{14}$ Hz
b. $f = 2.54 \times 10^{14}$ Hz
c. $f = 3.24 \times 10^{14}$ Hz
d. $f = 3.55 \times 10^{15}$ Hz
e. $f = 2.29 \times 10^{15}$ Hz

12. Which of these pairs of values of a and b correctly normalizes the wave function **and** can result, at some instant of time, in a zero probability density at the middle of the well (*i.e.*, at $x = L/2$)?

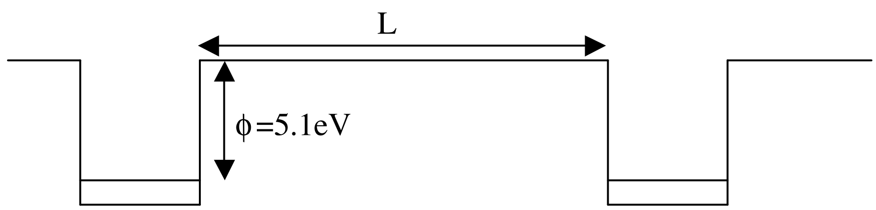
a. $a = b = 1/\sqrt{2}$
b. $a = b = 1/2$
c. $a = \sqrt{(2/3)}$, $b = \sqrt{(1/3)}$
d. $a = \sqrt{(2/3)}$, $b = -\sqrt{(1/3)}$
e. No values of a and b will ever result in a zero probability density at the middle of the well.

13. Suppose, now, that $a = 0.399$ and $b = 0.917$. If we measure the energy, what is the probability, P_3, of obtaining E_3?

a. $P_3 = 1.00$
b. $P_3 = 0.399$
c. $P_3 = 0.518$
d. $P_3 = 0.841$
e. $P_3 = 0.917$

The next two questions pertain to the following situation:

The work function (energy needed to remove an electron) of gold is 5.1 eV. Two pieces of gold (at the same potential) are separated by a distance, *L*.



14. For what value of *L* will the transmission probability for an electron to cross from one to the other be $T \approx 10^{-3}$? Assume that $G = 1$ in the formula for the tunneling probability.

a. $L = 0.001$ nm
b. $L = 0.02$ nm
c. $L = 0.1$ nm
d. $L = 0.3$ nm
e. $L = 4$ nm

15. Suppose we increase *L* by a factor of two from the value required for the transmission probability, *T*, to be $\approx 10^{-3}$. What is the new value of *T*?

a. $T \approx 10^{-6}$
b. $T \approx 0.5 \times 10^{-3}$
c. $T \approx 1 \times 10^{-3}$
d. $T \approx 2 \times 10^{-3}$
e. $T \approx 0.03$

The next two questions are related:

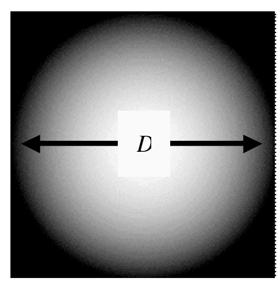
16. An electron is confined in a 3-dimensional rectangular box ($V = 0$ inside, and $V = \infty$ outside) with sides $L = 4$ nm, 4 nm, and 5 nm. What minimum energy, E_-, must a photon have in order to excite the electron out of its ground state. (The electron absorbs the photon.)

a. $E_- = 0.015$ eV
b. $E_- = 0.045$ eV
c. $E_- = 0.071$ eV
d. $E_- = 0.125$ eV
e. $E_- = 0.241$ eV

17. Now we put 10 electrons into the box. Assuming the total energy of the system is as low as possible, and **including the effects of spin**, how many electrons have the energy of the *second* excited state?

a. None
b. 1
c. 2
d. 4
e. All 10

18. Consider a wave function that is a spherical blob with diameter, D, as shown. The average value of its kinetic energy (if one makes a large number of measurements of identical systems) is $<KE_0>$. Now, shrink the wave function in all three dimensions, so that it is a similar spherical blob with diameter *half* D. What will be the new average kinetic energy, $<KE>$?



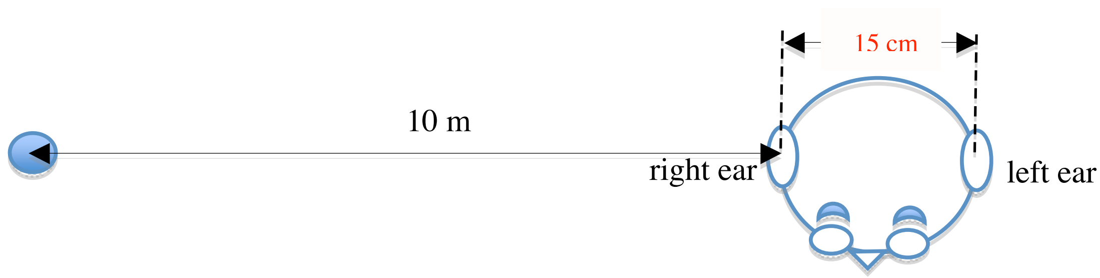
a. $<KE> = <KE_0>$
b. $<KE> = 2<KE_0>$
c. $<KE> = 4<KE_0>$

19. A hydrogen atom is initially at rest (approximately), in an excited state of unknown quantum number, n. The electron, drops to the next lower energy level, emitting a photon. Estimate the ***largest possible*** recoil velocity of the atom.

a. 0 (the atom does not recoil when it emits a photon)
b. 3.26 m/s
c. 121.6 m/s

The next two questions pertain to the following situation:

You are sitting 10 meters from a musician (left-most dot) playing an instrument with a steady note at some unknown frequency *f*. You are facing in a direction perpendicular to the direction of the musician, as shown in the figure below (not to scale):

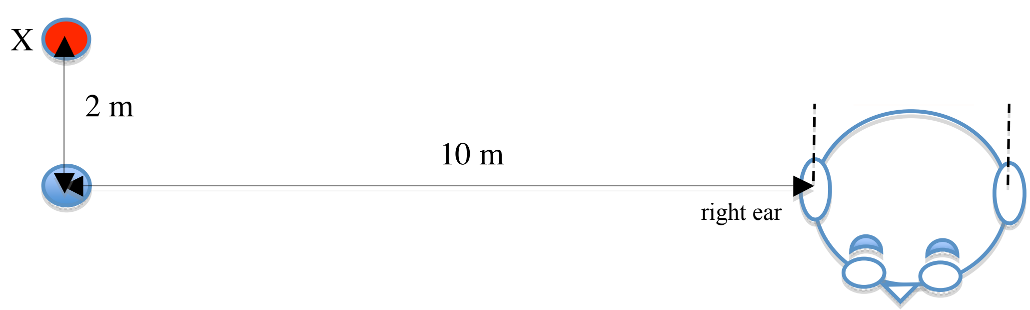


The speed of sound is 346 m/sec and the diameter of your head (*i.e.*, distance between your eardrums) is 15 cm.

20. Suppose that at some instant in time the pressure exerted by the sound wave on your right eardrum is at a maximum and the pressure exerted by the sound wave on your left eardrum is zero. What is the lowest possible frequency, *f*, of the note that the musician is playing? *Hint: Sketch the pressure at the chosen instant, p(x), as a function of position, and identify the locations of the two ears*.

a. $f = 577$ Hz
b. $f = 1153$ Hz
c. $f = 2307$ Hz

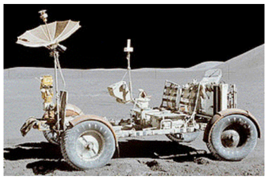
21. A second musician ("X") joins in and they both play a steady middle-C note ($f = 278$ Hz) *in phase*. The second musician sits 2 meters away from the first musician in the perpendicular direction from the line between you and the first musician, as shown in the figure below.



The intensity that each musician produces at your right eardrum when they play alone is 2 W/m^2. What is the net intensity, *I*, at your right eardrum?

a. $I = 0$ W/m^2
b. $I = 0.8$ W/m^2
c. $I = 1.5$ W/m^2
d. $I = 6.2$ W/m^2
e. $I = 7.0$ W/m^2

22. The Apollo 11 mission landed on the Moon in 1969. Moon hoax enthusiasts often cite a lack of teloscopic evidence for hardware they left behind. The Hubble Space Telescope (HST) is the largest orbiting telescope, with a 2.4-meter aperture mirror. At closest approach, the HST-moon distance is 376,000 km.



By approximately what factor would we have to increase the HST mirror aperture to resolve the lunar rover left by the Apollo 11 astronauts under the most optimistic circumstances? Use a wavelength of 700 nm for the light being detected by the HST and require that we need to resolve 15 cm features in order to identify it.

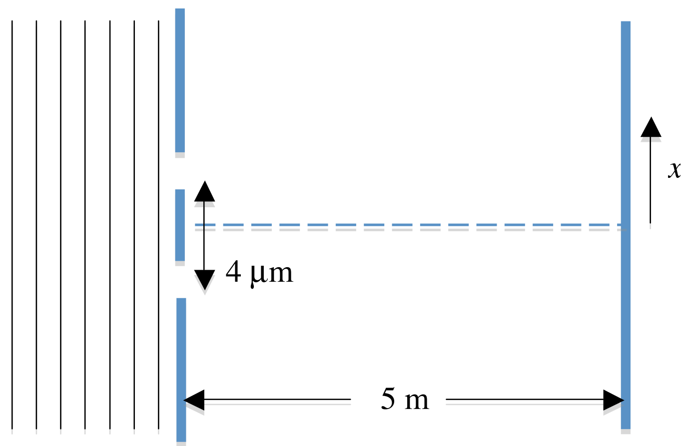
a. Factor = 10
b. Factor = 100
c. Factor = 1000
d. Factor = 10000
e. Factor = 100000

23. Light of unknown wavelength falls on a tiny pinhole. The pattern created by the pinhole has its first diffraction minimum at an angle 2° from the center line. In a second experiment light falls on a pinhole with a diameter that is half of that in the first experiment. What is the angle, θ_{min}, of the first diffraction minimum for the second (smaller) pinhole?

a. $\theta_{min} = 1°$
b. $\theta_{min} = 2°$
c. $\theta_{min} = 4°$
d. $\theta_{min} = 8°$
e. $\theta_{min} = 16°$

The next two questions pertain to the following situation:

In a two-slit interference experiment, a viewing screen is placed 5 meters directly behind two slits separated by 4 μm. Coherent, monochromatic light of wavelength λ = 700 nm emerges (in phase) from the slits. (Assume the slit width is very small compared to the wavelength λ.)



24. At what value of x on the screen does the largest-order intensity maximum occur (*i.e.*, the one that is the ***farthest*** from the center line)?

a. x = 1.2 m
b. x = 4.4 m
c. x = 5.0 m
d. x = 9.0 m
e. x = 15.7 m

25. What happens to the separation between the existing intensity maxima on the screen as we ***increase*** the slit spacing?

a. The separation decreases.
b. The separation increases.
c. There is no change.

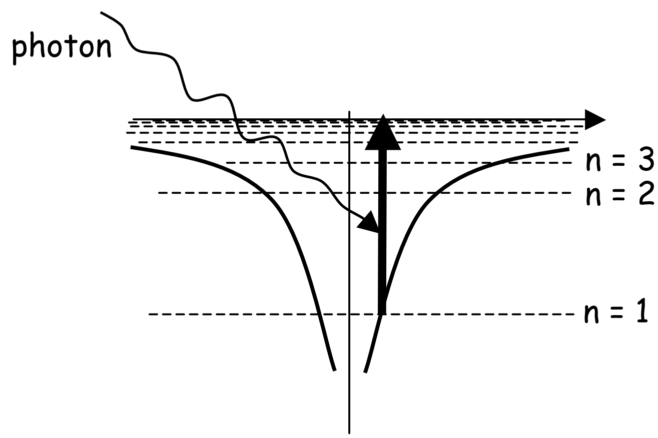
The next two questions pertain to the following situation:

Consider doubly ionized Lithium (Li^{++}), which has 1 electron orbiting a charge +3 nucleus.

26. Compare $a_{o,Li}$, the most likely distance for the electron in a Li^{++} atom to be from the nucleus, with $a_{o,H}$, the most likely distance for the electron in a hydrogen atom to be from the nucleus, assuming the electron is in the ground state in both cases. Which of the following is true?

a. $a_{o,Li} < a_{o,H}$
b. $a_{o,Li} = a_{o,H}$
c. $a_{o,Li} > a_{o,H}$

27. What is the maximum wavelength, λ_{max}, of light that would completely ionize the Li^{++} (*i.e.*, free the electron from the nucleus)?



a. $\lambda_{max} = 0.665$ nm
b. $\lambda_{max} = 10.1$ nm
c. $\lambda_{max} = 21$ nm
d. $\lambda_{max} = 137$ nm
e. $\lambda_{max} = 487$ nm

28. Which of the following statements is true?

a. An ideal metal conducts because each electron 'belongs' to every nucleus in the crystal lattice, while in an ideal insulator, each electron is localized to a single nucleus.
b. Metals conduct much better than insulators because, per gram of material, metals have orders of magnitude more electrons.
c. At sufficiently low temperatures, (intrinsic) semi-conductors are effectively insulators.

29. A Ca atom (atomic number = 20) is in the ground state. Light is shined on the atom, exciting the most energetic electron. Which of the following are possible quantum numbers (n,l,m) of this ***excited*** electron? We omit the electron spin quantum number.

a. (4, 0, 0)
b. (4, 1, -1), (4, 1, 0), and (4, 1, 1)
c. (5, 2, +1) and (5, 2, -1)
d. All of the above
e. None of the above

30. You are given a collection of quantum dots (treat as 1-D infinite square wells) and a collection of diatomic molecules (treat as simple harmonic oscillators). You find that the same wavelength of light will excite both the quantum dots and the molecules from their ground states to their first excited states. What is the ratio of the photon energies required to further excite each system ***from the first <u>excited</u> state to the second <u>excited</u> state***?

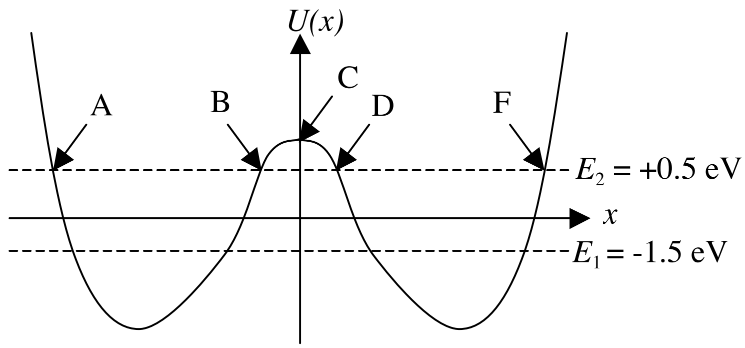
a. $E_{\text{quantum dot}}/E_{\text{molecule}} = 1$
b. $E_{\text{quantum dot}}/E_{\text{molecule}} = 6/5$
c. $E_{\text{quantum dot}}/E_{\text{molecule}} = 5/3$
d. $E_{\text{quantum dot}}/E_{\text{molecule}} = 15/2$
e. The information given is not sufficient to answer this question.

31. Electron spin resonance (ESR) is a technique much like nuclear magnetic resonance (NMR), except that it relies on using radio-frequency photons to flip the spin of an electron in a magnetic field. If the magnetic field applied to the electrons is increased from 0.010 Tesla to 0.011 Tesla, how much, Δf, will the transition frequency change?

a. Δf = 7 MHz
b. Δf = 14 MHz
c. Δf = 28 MHz

The next three questions pertain to the following situation:

An electron is moving in the potential, *U(x)*, shown to the right. This potential is an even function of x. The energies, $E_1 = -1.5$ eV and $E_2 = +0.5$ eV, of the two lowest energy states are indicated by the dashed lines. Five x values are labeled A-F in the figure. $\psi_1(x)$ is the wave function of the ground state, and $\psi_2(x)$ is the wave function of the first excited state.



32. Which one of the following statements is **not** true?

a. $\psi_1(\text{A}) = \psi_1(\text{F})$

b. $$\left.\frac{d\psi_1}{dx}\right|_{x=C} = 0$$

c. $\psi_2(\text{A}) = \psi_2(\text{F})$

d. $$\left.\frac{d|\psi_2|^2}{dx}\right|_{x<A} > 0$$

e. Both ψ_1 and ψ_2 have exponential x dependence in the region B < x < D.

33. Which wave function penetrates farther into the region x > F? That is, for which wave function is $\psi(x) / \psi(\text{F})$ larger when x > F?

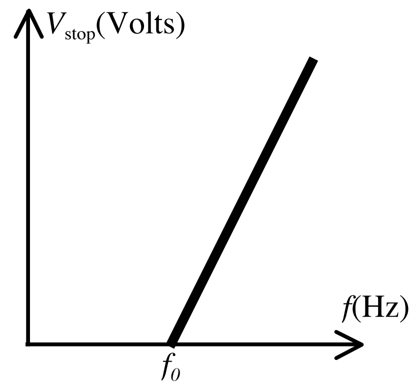
a. ψ_1
b. ψ_2
c. They are the same.

34. If the system is prepared in a superposition of ψ_1 and ψ_2, at what frequency does the probability density oscillate?

a. $f = 4.8 \times 10^{14}$ Hz
b. $f = 3.6 \times 10^{14}$ Hz
c. $f = 1.2\ 4 \times 10^{14}$ Hz

The following two questions refer to this situation:

The graph at the right shows the results of a photoelectric effect experiment in which the stopping voltage was measured for several frequencies of light.
The slope of the line is
4.0×10^{-15} Volts/Hz, and the *x*-intercept is $f_0 = 6.0\times10^{14}$ Hz.



35. What is the work function, Φ, of the material?

a. Φ = -6.0 eV
b. Φ = -4.0 eV
c. Φ = +2.4 eV
d. Φ = +4.0 eV
e. Φ = +6.0 eV

36. What value of Planck's constant, *h*, does this data yield?

a. $h = 6.0\times10^{-34}$ J·s
b. $h = 6.2\times10^{-34}$ J·s
c. $h = 6.4\times10^{-34}$ J·s
d. $h = 6.6\times10^{-34}$ J·s
e. $h = 6.8\times10^{-34}$ J·s

Did you bubble in your name, exam version and network-ID?
Check to make sure you have bubbled in all your answers.