Last Name:＿＿＿＿＿＿＿＿＿＿＿＿＿First Name＿＿＿＿＿＿＿＿＿＿ID＿＿＿＿＿＿＿＿＿＿＿
Discussion Section:＿＿＿＿＿＿＿Discussion TA Name:＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿＿

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 OF THE ABOVE STEPS. YOUR GRADE DEPENDS ON IT!*

*Before starting work, check to make sure that your test booklet is complete.  You should have 14 pages (35 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 165 points, 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.

*The next two questions pertain to the following situation:*

Two speakers are placed in the corners of a room and heard from a chair that is equidistant from each speaker, as shown in the diagram. The speakers are driven in phase at 2 kHz.



speaker          speaker
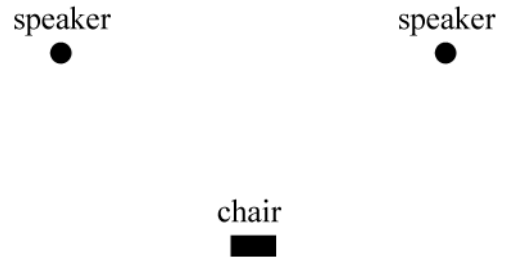
chair

1. The power outputs of the speakers are controlled separately.  The sound intensity at the chair is 8 W/m$^2$ when only the left speaker is on, and it becomes 200W/m$^2$ when both speakers are on.  What is the intensity at the chair when only the right speaker is on?

a.  14 W/m$^2$
b.  64 W/m$^2$
c.  128 W/m$^2$
d.  192 W/m$^2$
e.  197 W/m$^2$

2. The frequency of the speakers is now increased to 4 kHz while keeping the intensities from each speaker constant.   What happens to the total intensity at the chair when both speakers are on?

a.  decreases
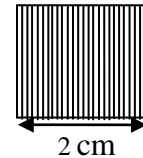b.  increases
c.  stays the same

3. A microscope is used to view a computer chip for possible flaws.  To do this job, it is necessary to be able to resolve two "point objects" that are 2 μm apart.  If  the working distance between the microscope lens and the chip (i.e., its focal length) is 3 cm, what lens diameter is required to resolve the objects? Assume a typical wavelength of 510 nm for visible light.

a.  0.24 cm
b.  0.47 cm
c.  0.93 cm
d.  2 cm
e.  2.93 cm

*The next two questions pertain to the following situation:*

4.  A spectrometer with grating size of 2 cm and a total of 10,000 lines is used to analyze the spectrum of a star.  The light is normally incident on the grating and illuminates the whole grating.  A sharp spectral line is observed in second order at an angle of $45^o$ from normal incidence.  What is the wavelength of this starlight?

a.  192 nm
b.  354 nm
c.  383 nm
d.  707 nm
e.  1410 nm

2 cm

5.  What is the effect of illuminating only the right half of the grating?

a.  the width of the observed spectral line increases by a factor of 2.
b.  the width of the observed spectral line decreases by a factor of 2.
c.  the width stays the same, but the total number of diffraction orders decreases.

6.  For a proton in the ground state of a 1-dimensional infinite square well, what is the probability of finding the proton in the central 2% of the well?

a.  0.01
b.  0.02
c.  0.03
d.  0.04
e.  0.05

7.  Electrons of wavelength 1.5 nm are emitted from a material when light of wavelength 350nm is incident on it.  What is the work function of this material?

a.  −3.1 eV
b.  0 eV
c.  0.7 eV
d.  2.9 eV
e.  3.5 eV

*The next two questions pertain to the following situation:*

Atoms of mass *m* are known to be moving with a velocity 2.02 m/s. The atoms are directed onto two slits, each 2 μm in width and separated by 12 μm. The following interference pattern is observed on a detector at a distance of 0.09 m.
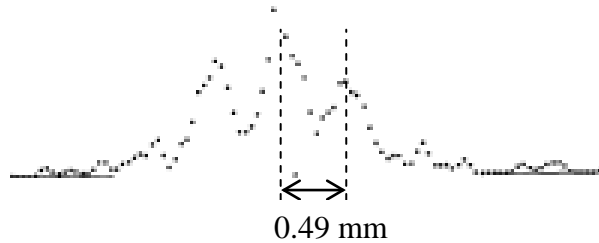


0.49 mm

8. Estimate the mass *m* of the atoms.

a. $8.0 \times 10^{-28}$ kg
b. $3.0 \times 10^{-26}$ kg
c. $5.0 \times 10^{-27}$ kg
d. $4.4 \times 10^{-24}$ kg
e. $2.8 \times 10^{-23}$ kg

9. If the kinetic energy of the atoms is halved, what will happen to the fringe spacing Δy (0.49mm in the figure above)?

a. Δy → 0.25 mm
b. Δy → 0.35 mm
c. Δy → 0.49 mm (i.e., no change)
d. Δy → 0.69 mm
e. Δy → 0.98 mm

***The next three problems refer to the situation below.***

Consider a one-dimensional infinite square well. The second excited state (the third level) of an electron has an energy of 12.9 eV, measured from the bottom of the well. Be sure to consider electron spin.

10. What is the maximum number of electrons that can have this particular energy?

a. 1
b. 2
c. unlimited

11. What is the wavelength of the light emitted when the electron makes a transition from the second excited to the first excited state?

a. 0.51 nm
b. 87 nm
c. 173 nm
d. 216 nm
e. 501 nm

12. Now expand the well width by a factor of 2. What is the energy of the second excited state?

a. 3.2 eV
b. 5.7 eV
c. 9.1 eV
d. 25.8 eV
e. 666 eV

13. MRI detects the hydrogen nuclei (protons) in your body. What magnetic field is required to produce a transition frequency of 25 MHz?

a. 0.59 Tesla
b. 1.17 Tesla
c. 3.45 Tesla

14. Which of the following statements about a particle trapped in the potential shown below is *false*?
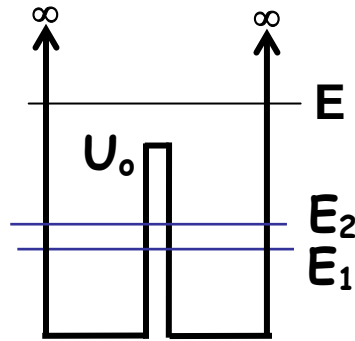


a.  A wavefunction with energy $E > U_o$ has exponentially decaying regions.
b.  If most of the probability density of the particle is in the left half, the particle is in a superposition of at least two eigenstates.
c.  If the particle is in a superposition of the ground state and the first excited state (at $E_1$ and $E_2$) such that its probability density is initially on the left, there is a finite probability that this density will "tunnel" to the right at a later time.

15.  An argon atom ($Z = 18$) is in its ground state.  What are the possible quantum numbers of the electron with the highest energy?

a.  (3 0 -1), (3 0 0), (3 0 +1)
b.  (3 1 -1), (3 1 0), (3 1 +1)
c.  (4 0 0)
d.  (4 1 -1), (4 1 0), (4 1 +1)
e.  cannot be determined from the information given

16.  A particle in an infinite square well (SW) has the same ground-state energy as the same particle in a simple harmonic oscillator (HO) potential. All energies are measured from the bottom of the potentials.  What is the ratio of energies for the <u>first excited states</u> of these systems; i.e., $E^{SW}/ E^{HO}$?

a.  1
b.  4/3
c.  2
d.  9/5
e.  The information given is not sufficient to answer this question.

***The next three questions pertain to the following situation:***

An electron in an infinite potential well occupies the following wavefunction at time $t = 0$ :

U(x)
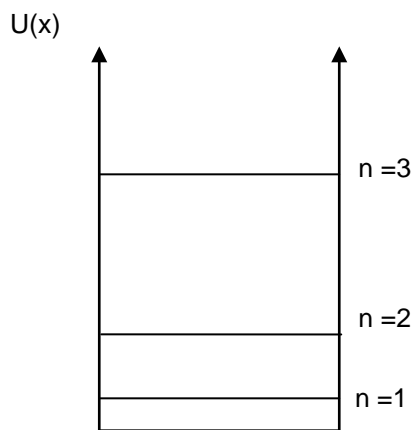
$$\Psi(x,0) = 0.5\, \psi_1(x) + A\, \psi_2(x).$$

Here, $\psi_1$ and $\psi_2$ are normalized wavefunctions of the states $n = 1$ and $n = 2$ with corresponding energies $E_1$ and $E_2$. A is a constant which must be chosen to normalize $\Psi$.

n =3

n =2

n =1

17. If we measure the electron's energy, what would be the result?

a. $E_1$ or $E_2$
b. A definite energy between $E_1$ and $E_2$
c. One cannot determine with the information given.

18. When a measurement is made on the electron, what is the probability of finding it in the state with $n = 2$?

a. 0.25
b. 0.50
c. 0.75
d. 0.87
e. 1.00

19. If the energy of the $n = 1$ state is $E_1 = 4$ eV, after what time t does the wave function come back to the form described at $t = 0$ (apart from an arbitrary phase factor)?

a. $3.4 \times 10^{-16}$ s
b. $4.1 \times 10^{-16}$ s
c. $4.8 \times 10^{-16}$ s
d. $5.9 \times 10^{-16}$ s
e. It will never return to the original form.

***The next two questions pertain to the following situation:***
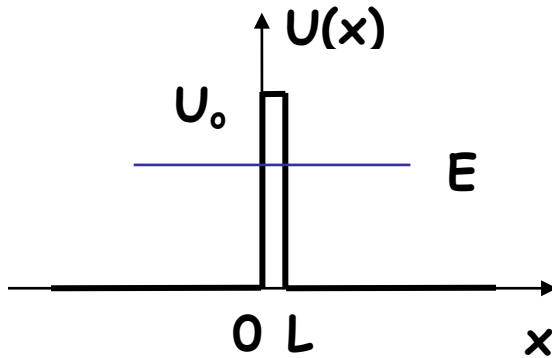


20.  An electron with total energy 5 eV approaches a potential barrier of height 20 eV.  If the probability that the electron tunnels across the barrier is 0.03, what is the width $L$ of the barrier?

a.  0.0116 nm
b.  0.116 nm
c.  1.16 nm
d.  11.6 nm
e.  116 nm

21.  Define $K = \sqrt{\dfrac{2m}{\hbar^2}(U_0 - E)}$ . If the barrier is now increased from $L$ to $3L$, by what factor does the transmission probability <u>change</u>?

a.  $\exp(-2KL)$
b.  $\exp(-4KL)$
c.  $\exp(-6KL)$

22.  A molecule in its lowest energy eigenstate is described by the wavefunction $\psi = \psi_0(x)e^{i\omega t}$. Its *probability density*

a.  oscillates with a time period of $2\pi/\omega$.
b.  remains stationary.
c.  satisfies the time-dependent Schrodinger equation.

23.  The Nitrogen atom in the ammonia molecule ($NH_3$) can have two equivalent positions, giving rise to a splitting of the lowest vibrational state.
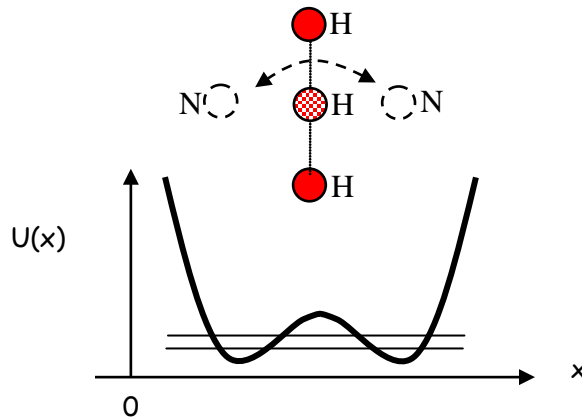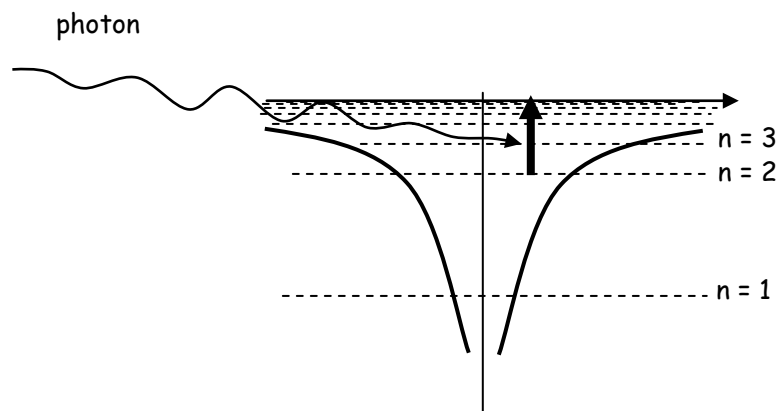


The frequency of the photons emitted by the $NH_3$ maser is 43.5 GHz. What is the energy splitting between the ground and first excited states of the $NH_3$ molecule?

a.  $3.1 \times 10^{-3}$ eV
b.  $1.8 \times 10^{-4}$ eV
c.  $4.6 \times 10^{-5}$ eV

24.  A hydrogen atom is in its $n = 2$ state.  Calculate the maximum wavelength of light that will ionize the atom (*i.e.*, free the electron from the nucleus).

a.  $\lambda_{max} = 0.665$ nm
b.  $\lambda_{max} = 17.6$ nm
c.  $\lambda_{max} = 91$ nm
d.  $\lambda_{max} = 365$ nm
e.  $\lambda_{max} = 487$ nm

25.  An undergraduate student uses the Physics 214 Lab 4 diffraction-grating spectrometer to observe the emission spectrum from a hydrogen-gas discharge tube, as shown in the figure below. The diffraction grating has a line spacing of 1 μm. The student wishes to observe the $n_i = 5$ to $n_f = 2$ emission line of hydrogen in first order.



**Hydrogen Gas
Discharge Tube**                                               **Diffraction
Grating**
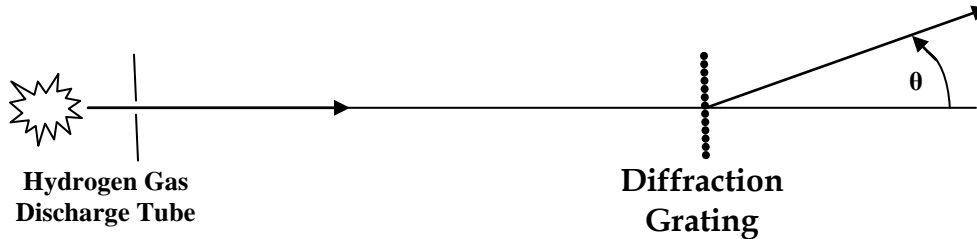
At what angle θ will the student observe this hydrogen emission line?

a.  $\theta = 12.8^o$
b.  $\theta = 25.7^o$
c.  $\theta = 45.2^o$
d.  $\theta = 76.5^o$
e.  The first order is greater than $90^o$.

26.  Ultraviolet light of wavelength 350 nm is directed at a piece of aluminum (work function 4.1 eV), and the current of emitted electrons is measured.  What happens to the current of emitted electrons if the power of the light is doubled?

a.  Nothing – no electrons are emitted in either case.
b.  There is a current, but it is unaffected by the intensity of the light.
c.  The current doubles.

27.  Which one of the following statements is the most accurate?  Insulators are many orders of magnitude less conducting than metals because _____

a.  insulators have no partially filled bands.
b.  per gram of material, the total number of electrons in metals is much higher.
c.  at room temperature, all the electrons in a metal are in a single quantum state, which therefore suffers no resistance.

***The next two problems refer to the situation below.***

An electron is trapped in a 2-dimensional quantum well with sides 0.75 nm, as shown in the figure below.



0.75 nm

0.75 nm
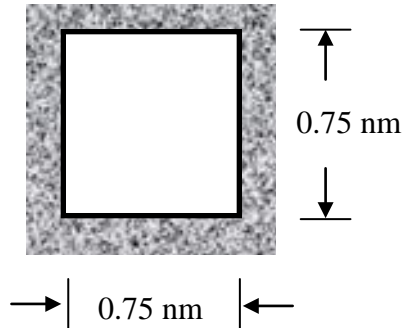
28.  What is the energy of the <u>first excited state</u> for a single electron in this quantum well?

a.  0.67 eV
b.  1.17 eV
c.  1.88 eV
d.  2.41 eV
e.  3.34 eV

29.  For this problem be sure to consider the effects of spin. If $E_{min}$ is the minimum energy that *one electron* can have in this well, what is the minimum <u>total energy</u> that *4 electrons* can have in this well?  (Hint: It may help to calculate $E_{min}$.)

a.  $4 E_{min}$
b.  $5 E_{min}$
c.  $6 E_{min}$
d.  $7 E_{min}$
e.  $8 E_{min}$

30.  Consider an ionized $^3$He atom (2 protons, 1 neutron, and 1 electron). What is the energy of the n = 3 state?

a.  −1.5 eV
b.  −6.0 eV
c.  −13.6 eV

***The next three questions pertain to the following situation:***

Consider an electron in a double-well potential, analogous to a diatomic molecule. The wave functions with the two lowest energies are shown. Energies are not drawn to scale.
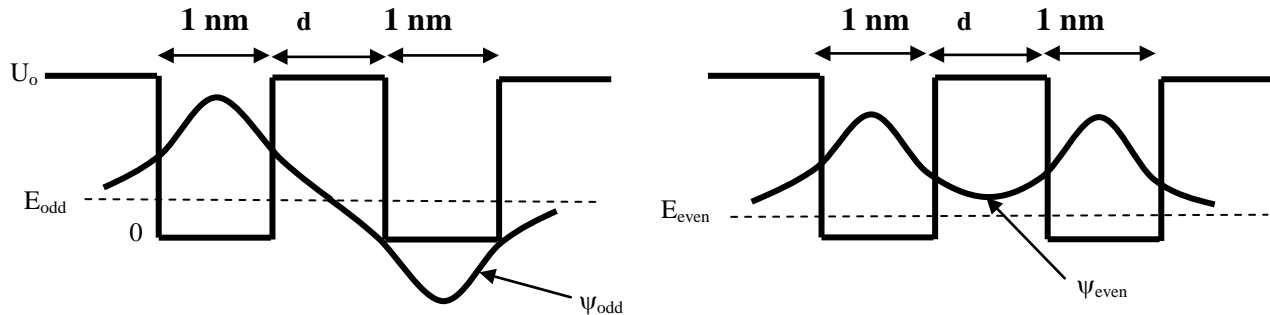


31. What happens to the magnitude of the energy splitting ($\Delta E = |E_{odd} - E_{even}|$) as the two wells are pushed together; i.e., as the width d of the central barrier is decreased? (Hint: What happens to the oscillation frequency if the electron started out localized in one well?)

a. $\Delta E$ increases.
b. $\Delta E$ decreases.
c. $\Delta E$ does not change.

32. Assuming that $E_{odd}$ and $E_{even}$ are <u>much less</u> than $U_o$, <u>estimate</u> the energy splitting of these two states as d approaches zero. (Hint: Draw the wave functions when d is very small.)

a. 0.3 eV
b. 1 eV
c. 2 eV
d. 5 eV
e. 9 eV

33. The electron is put into the first excited state, and at some later time emits a photon. We then make a measurement to determine which well the electron is in. Which of the following statements is <u>false</u>?

a. Just prior to the measurement, the electron is simultaneously in the left well and the right well.
b. We are equally likely to find the electron in the left well or the right well.
c. The probability of finding the electron in the left well oscillates in time between 0 and 1.

34.  An electron in the 3d state of the hydrogen atom has a radial part of the wave function of the form A $r^2$ exp(-r/$3a_o$).  What is the most likely radius at which the electron would be found?

a.  $2a_o$
b.  $3a_o$
c.  $4a_o$
d.  $5a_o$
e.  $9a_o$

35. A photon localized to a _short pulse_ (duration = 1 ns, equivalent to a length of 0.3 m) is sent into the interferometer shown. The top arm is 1-m long, the right arm is 2-m long.
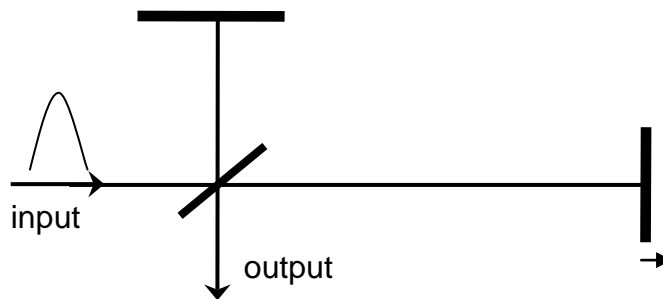


As we slightly move out the right mirror, what will happen to the probability that the photon leaves the interferometer by the port marked "output"?

a.  The probability will decrease.
b.  The probability will stay constant at ½. There will be no interference in this arrangement, i.e., half the light will come out the bottom "port," and half will go back toward the input.
c.  The probability will stay constant at 1, i.e., the photon always exits to the port labeled "output".

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