Last Name:_____First Name_____NetID_____
Discussion Section:_____Discussion TA Name:_____

Instructions—
Turn off your cell phone and put it away.
Keep your calculator on your own desk. Calculators may not be shared.
This is a closed book exam. You have ninety (90) minutes to complete it.

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*.

*Before starting work, check to make sure that your test booklet is complete. You should have 11 **numbered pages** plus two Formula Sheets at the end.*

*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 expulsion.**

Exam Grading Policy—

The exam is worth a total of ??? 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 following three problems pertain to the following situation

At a rock concert, two stereo speakers are driven in phase by an amplifier. Wolfgang is seated at a distance r_1 from Speaker 1 and r_2 from Speaker 2, as shown below. The speed of sound is 330 m/s. He receives music at an intensity of $4W/m^2$ from each speaker individually.
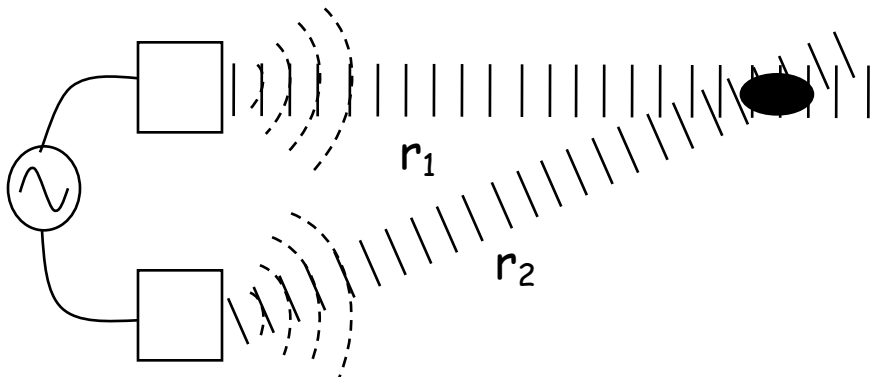
(Picture not to scale)

During the concert, a keyboard plays a note at a frequency of $f = 440Hz$. At Wolfgang's location, the phase difference between Speaker 1 and Speaker 2 at this frequency is $\varphi = 60°$ ($\pi/3$ radians).

1. If $r_2 = 100$ m, what is r_1?

a. 5.671 m
b. 18.983 m
c. 47.552 m
d. 73.125 m
e. 99.875 m

2. Wolfgang finds the keyboard note to be most annoying and seeks to eliminate hearing it by interference. He cannot change location, but he has a fancy set of headphones that act as a third source which emits sound at an intensity I_h and phase φ_h relative to the phase of the sound reaching him from Speaker 1. At what values of I_h and φ_h would Wolfgang experience complete destructive interference of the combined effects of the two speakers? (A phasor diagram could be useful.)

a. $I_h = 8$ W/m^2 , $\varphi_h = 120°$ ($2\pi/3$ radians)
b. $I_h = 8$ W/m^2 , $\varphi_h = 120°$ ($3\pi/4$ radians)
c. $I_h = 12$ W/m^2 , $\varphi_h = 150°$ ($5\pi/6$ radians)
d. $I_h = 12$ W/m^2 , $\varphi_h = 210°$ ($7\pi/6$ radians)
e. $I_h = 20$ W/m^2 , $\varphi_h = 120°$ ($3\pi/4$ radians)

3. Going back to the two speaker situation, now suppose that the speakers are adjusted such that Speakers 1 and 2 individually produce intensities of 4 W/m^2 and 6 W/m^2, respectively, at Wolfgang's location and that their relative phase is $\varphi = 90°$ ($\pi/2$ radians). At what intensity does Wolfgang hear their combined effect?

a. 0.2 W/m^2
b. 10.0 W/m^2
c. 12.3 W/m^2

4. Consider a pulse described by the function $y(x,t) = Ae^{-(x+\alpha t)^2/u^2}$, where x denotes distance and t denotes time, and A, α and u are all positive in sign. Which of the following is true?

a. The pulse moves along the positive x direction at a speed u.
b. The pulse moves along the negative x direction at a speed u.
c. The pulse moves along the negative x direction at a speed α.

The next two questions pertain to the following situation:
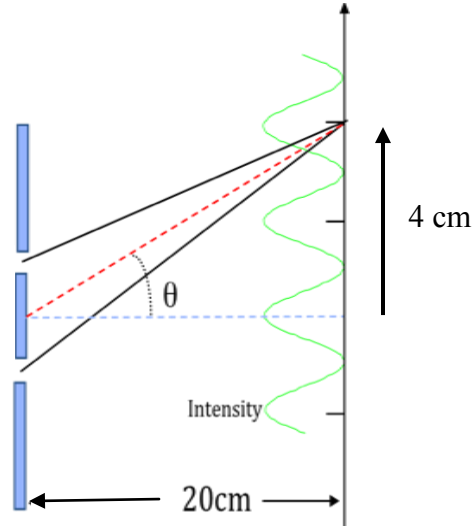
In a two-slit interference experiment, a viewing screen is placed 20 cm directly in front of the slits. Light of wavelength 640 nm emerges in phase from the two slits and the resulting <u>second principal maximum</u> on the screen lies 4 cm away from the center.

5. What is the spacing between the two slits?

a. 6.5 μm
b. 45.8 μm
c. 131.1 μm
d. 0.3 mm
e. 1.9 mm

6. If the light source is now adjusted such that the phase between the light emerging from the two slits is π/4, what happens to the image on the screen?

a. It stays the same; it is independent of the phase.
b. The whole image diminishes in brightness.
c. The whole image shifts.

The following three problems pertain to the same situation.

Normal-incidence red light with a wavelength of 590 nm is diffracted by a 5-cm wide grating with line spacing of 14 microns. Suppose the light illuminates only <u>one half</u> of the grating.

7. What is the closest wavelength to the 590 nm light that can be resolved by this diffraction grating in the 3rd-order spectrum?

a. 593.07 nm
b. 590.11 nm
c. 590.33 nm
d. 591.66 nm
e. 592.88 nm

8. How much will the intensity of the 2nd-order principal diffraction peak change if now the light illuminates the entire grating?

a. The intensity will stay the same.
b. The intensity will increase by factor 2.
c. The intensity will increase by factor 4.

9. Suppose we send now a beam of electrons on the same diffraction grating. In order to have the interference maxima at exactly the same position as was observed with light, one has to make sure that

a. the energy of the electrons is the same as that of the photons.
b. the area which the electronic beam covers on the grating is the same.
c. the de Broglie wavelength of the electrons is the same as that of the photons.

The following two problems pertain to the same situation.

10. A light beam illuminates the surface of barium, which has the workfunction of 2.48 eV. Due to the illumination some electrons get ejected from the piece of barium. The kinetic energy of the electrons is $\leq 10^{-18}$ J. Find the wavelength of the light.

a. 100 nm
b. 116 nm
c. 120 nm
d. 142 nm
e. 163 nm

11. What is the voltage required to stop the ejected electrons?

a. 2.48 V
b. 3.77 V
c. 6.25 V

12. The power received by your TV satellite antenna is 1 mW. If frequency of the signal is 8 GHz, how many photons arrive at the antenna every second.

a. 213
b. 8×10^8
c. 2×10^{20}

13. A laser with wavelength 600 nm is incident from below on a completely absorbing bead weighing 0.02 g. What laser power is required to suspend the bead against gravity?

a. 10 kW
b. 30 kW
c. 60 kW
d. 90 kW
e. 110 kW

The next four questions are related.

A blue laser (400 nm) and a red laser (600 nm)
are directed into a Michelson interferometer,
initially with equal path lengths, so that all the
light exits via the bottom port.
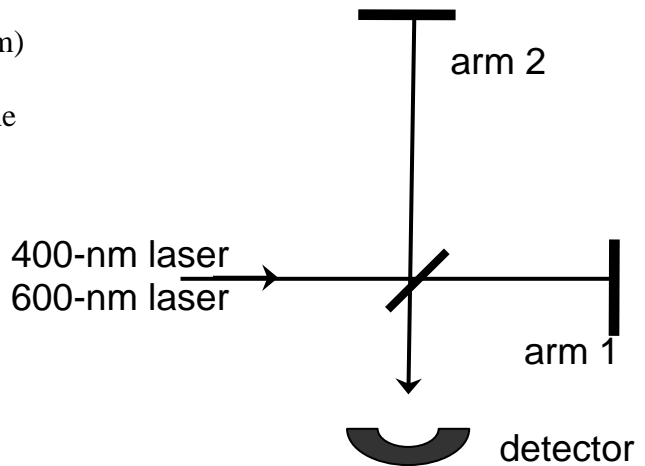
14. What is the smallest displacement δx
of the right mirror so that again all of the
light comes out the bottom? Hint: Sketch
$I(\delta x)$ for both wavelengths.

a. 200 nm
b. 400 nm
c. 600 nm
d. 1,000 nm
e. 2,400 nm

15. We now place a filter in the top arm that passes only red light, while in the right arm
we place a filter that passes only blue light. What do we observe at the bottom output as
we vary δx?

a. The output oscillates between purple (equal red and blue contributions) and black (no
light).
b. The output oscillates between red and blue.
c. There is a constant-intensity purple light at the output (i.e., equal red and blue
contributions).

16. Now we turn off the blue laser, leaving only the red laser (600 nm), and remove all
the filters. Suppose we make $L_1 = L_2 = 0.1$ m (these are the distances from the
beamsplitter to the mirrors) and place one of the arms in a medium with refractive index
$n = 1 + 3 \times 10^{-6}$, but keep the other arm in vacuum. How will the intensity at the bottom
detector change as compared to the case for which both of the arms are in vacuum?
        I_A: both arms in vacuum
        I_B: one arm in vacuum and the second arm in medium with $n = 1 + 3 \times 10^{-6}$

a. $I_A = I_B$
b. $I_A > I_B > 0$
c. $0 < I_A < I_B$

This problem is related to the previous ones.

17. Now consider only the red laser, which produces intensity I_0 incident on the beamsplitter. Let's say that now one of the mirrors reflects all of the light while the other reflects only a fraction R of the intensity. What is the maximum intensity observed at the bottom port, as δx is varied?

a. $\frac{I_0}{4}\left(1+\sqrt{R}\right)^2$

b. $\frac{I_0}{4}(1+R)$

c. $\frac{I_0}{4}\left(1+\sqrt{R}\right)$

d. $\frac{I_0}{4}(1+R)^2$

e. $\frac{I_0}{4}\left(1+R^2\right)$

18. You conduct an experiment in which you shine a beam of electrons of momentum $\vec{p} = p\hat{x}$ on a slit of width a and observe the resulting diffraction pattern.
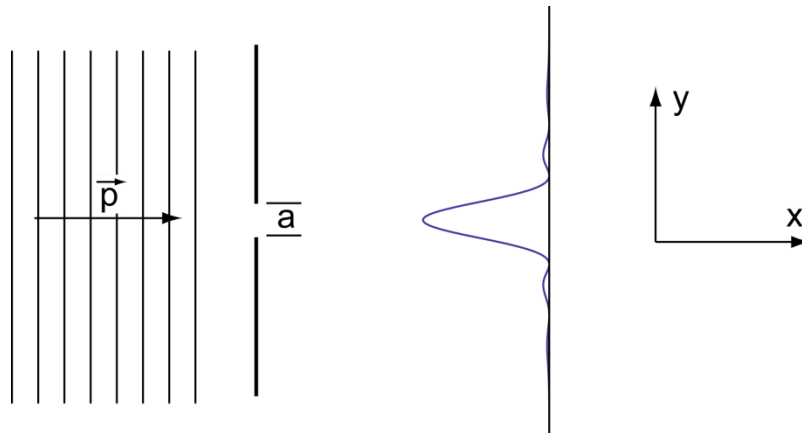
If you now vary the slit width and the electron momentum, which of the following statements is true?

a. The diffraction pattern is unchanged if we double the electron momentum and slit width by a factor of two.
b. Passing the electrons through the slit introduces uncertainty in the y-momentum proportional to $1/a$. Therefore, reducing a results in a broader diffraction pattern.
c. If instead of electrons, we accelerate protons (~2000 times more massive than an electron) to the same kinetic energy as the electrons, the diffraction pattern will become broader.

The next four questions are related.

19. An electron is trapped in a 1-D (effectively infinite) potential well of width 6 nm. The electron is initially excited to the <u>second</u> <u>excited</u> state. If the electron decays to the <u>first</u> <u>excited</u> state by emitting a photon, what is the wavelength of the photon?

a. 5.38 nm
b. 6 nm
c.   13.2 μm
d.   23.7 μm
e.   29.8 μm

20. In the first excited state, what is the probability of finding the electron somewhere between 1.4 to 1.6 nm?

a. 6.2%
b. 3.3%
c. The answer depends on precisely *when* the measurement is made.

21. Assuming you found the electron in that interval, what would be the uncertainty in its <u>velocity</u> after the measurement?

a. 0
b. 1.2×10^5 m/s
c. 5.8×10^5 m/s

22. Finally, we replace the electron by a muon (essentially a heavy electron, with the same charge the electron has, but $m_\mu = 209\ m_e$). If the particle is in the ground state of the potential well, what is its wavelength?

a. 0.029 nm
b. 0.057 nm
c. 12 nm
d. 1254 nm
e. 2508 nm

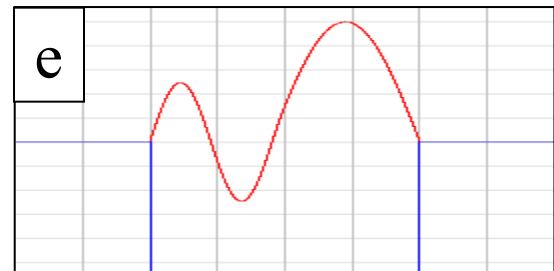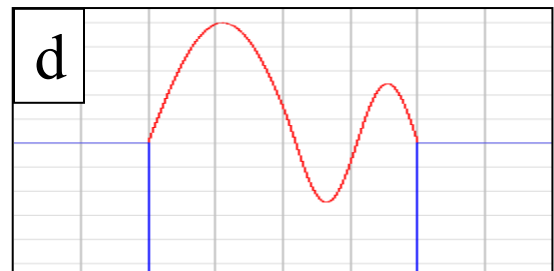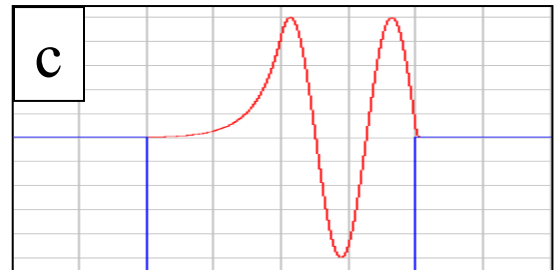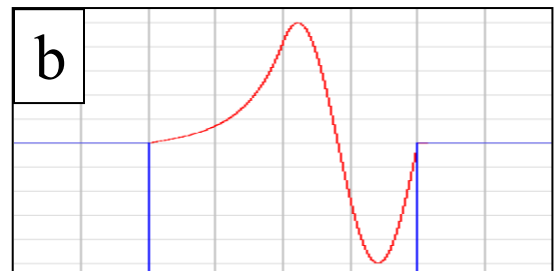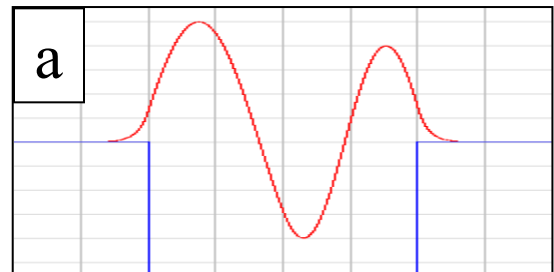*The next two problems are related.*

Consider particle confined in an asymmetric infinite potential well, as shown here. The horizontal lines represent the energy levels E_1 (ground state), E_2, and E_3.
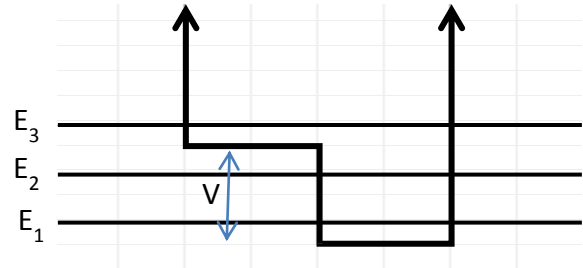
23. Which of the following wave functions might represent the <u>second</u> excited state?

a.

b.

c.

d.

e.

24. Which of the following statements is correct?

a.   In the ground state the particle has no chance to be found in the left-hand side of the well.
b.   In the first excited state the wavefunction is anti-symmetric.
c.   Lowering the height V of the step (see diagram) will lower the ground state energy E_1.

25. The figure below shows the intensity pattern produced by light passing through multiple slits. The plot shows the measured intensity, in units of the single slit intensity, vs. the angle θ. (Note: the number of slits shown in the picture does not necessarily correspond to this question.) Estimate the ratio of the slit spacing to the slit width. (d = slit spacing, a = slit width)
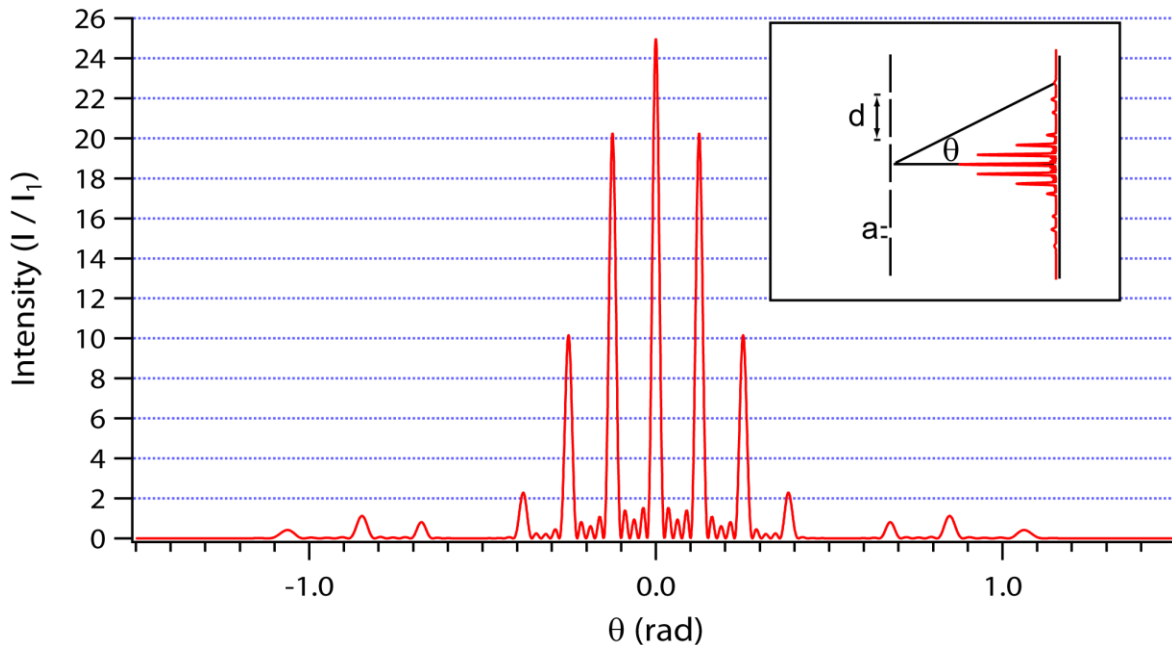
a. d/a = 1
b. d/a = 2
c. d/a = 4
d. d/a = 6
e. d/a = 8

26. You are designing an electron microscope capable of resolving two features separated by 1 nm. The f-number (f/D) of the microscope is 100. What is the accelerating voltage required to achieve this resolution?

a. 5,600 V
b. 8,400 V
c. 12,500 V
d. 17,800 V
e. 22,400 V
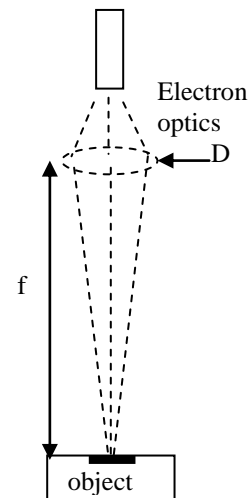
Solutions:

1. e

2. d

3. b

4. c

5. a

6. c

7. b

8. c

9. c

10. d

11. c

12. c

13. c

14. c

15. c

16. a

17. a

18. b

19. d

20. a

21. c

22. c

23. d

24. c

25. c

26. e