AFTER I GIVE THE SIGNAL TO BEGIN YOU CAN REMOVE THIS SHEET. DO NOT TURN IT IN!

162sp25t4a – Once the exam has officially started, remove the top sheet. The remaining sheets comprise your exam. It is each student's individual responsibility to ensure the instructor has received her or his completed exam. Any exams not received by the instructor earn zero points. Smart watches, phones, or other devices (except scientific calculators) are not permitted during the exam.

$1\ \text{kg}\cdot\frac{\text{m}}{\text{s}^2} = 1\ \text{N}$	$1\ \text{N}\cdot\text{m} = 1\ \text{J}$	$1\ \text{Pa} = 1\frac{\text{N}}{\text{m}^2}$	$1\ \text{W} = 1\ \frac{\text{J}}{\text{s}}$
$c = 2.998\times 10^{8}\frac{\text{m}}{\text{s}}$	$h = 6.626\times 10^{-34}\ \text{J}\cdot\text{s}$	$h = 4.136\times 10^{-15}\ \text{eV}\cdot\text{s}$	$1.602\times 10^{-19}\ \text{J} = 1\ \text{eV}$
$hc = 124\underline{0}\ \text{eV}\cdot\text{nm}$	$\hbar = \frac{h}{2\pi} = 1.0546\times 10^{-34}\ \text{J}\cdot\text{s}$	$\hbar = \frac{h}{2\pi} = 6.583\times 10^{-16}\ \text{eV}\cdot\text{s}$	$e = 1.602\times 10^{-19}\ \text{C}$
$\sigma = 5.67\times 10^{-8}\frac{\text{W}}{\text{m}^2\cdot\text{K}^4}$	$R_H = 1.09737\times 10^{7}\ \text{m}^{-1}$	$a_0 = 5.29\times 10^{-11}\ \text{m}$	$q_{proton} = +e$ & $q_{electron} = -e$
$m_e = 9.11\times 10^{-31}\ \text{kg} = 0.511\frac{\text{MeV}}{c^2}$		$m_p = 1.673\times 10^{-27}\ \text{kg} = 938\frac{\text{MeV}}{c^2}$ for this class assume $m_n = m_p$	
$\omega = \frac{2\pi}{T} = 2\pi f$	$k = \frac{2\pi}{\lambda}$	$E_\gamma = hf = \frac{hc}{\lambda}$ $\quad c = f\lambda$	$c = nv$ & $\lambda_n = \frac{\lambda}{n}$ & $f_n = f$
$p = \frac{E_\gamma}{c} = \frac{h}{\lambda} = \hbar k$	$I_{avg} = \frac{\mathcal{P}}{A}$	$\beta = \frac{v}{c}$	$\gamma = \frac{1}{\sqrt{1-\beta^2}}$
$\Delta t = \gamma\Delta t_0$	$L = \frac{L_0}{\gamma}$	$slope = \frac{1}{\beta}$	$t' = \gamma\left(t - \frac{vx}{c^2}\right)$
$x' = \gamma(x - vt)$	$u_x = \frac{u'_x + v}{1 + vu'_x/c^2}$	$u_y = \frac{u'_y/\gamma}{1 + vu'_x/c^2}$	$\Delta s^2 = (\Delta x^2 + \Delta y^2 + \Delta z^2) - c^2\Delta t^2$
$\vec{p} = \gamma m_{rest}\vec{u}$	$K = (\gamma - 1)E_{rest}$	$E_{rest} = m_{rest}c^2$	$E_{total} = K + E_{rest} = \gamma m_{rest}c^2$
$\mathcal{P}_{emitted} = \sigma A e T^4$	$f_{observed} = f_{source}\sqrt{\frac{1-\beta}{1+\beta}}$ Source & observer separate $\Rightarrow \beta > 0$.		$E_{total}^2 = p^2c^2 + (m_{rest}c^2)^2$
$\lambda_{max}T = 2.898\times 10^{-3}\ \text{m}\cdot\text{K}$	$E_n = nhf$	$I(\lambda,T) = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right]}$	$(1\pm\delta)^n = 1 \pm n\delta + \frac{n(n-1)}{2}\delta^2$
$\phi_{zinc} = 4.31\ \text{eV}$	$\phi_{copper} = 4.70\ \text{eV}$	$\phi_{sodium} = 2.46\ \text{eV}$ $\quad \phi_{aluminum} = 4.08\ \text{eV}$	$\phi_{iron} = 4.50\ \text{eV}$
$K_{max} = hf - \phi$	$K_{max} = e\Delta V_s$	$hf_c = \phi$	$\lambda' - \lambda_0 = \lambda_C(1 - \cos\theta)$
$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$	$E_n = -\frac{13.606\ \text{eV}}{n^2}$	$r_n = n^2 a_0$	$\lambda_C = \frac{h}{m_e c} = 2.426\times 10^{-12}\ \text{m}$
$mvr = n\hbar$	$F = \frac{k_e\lvert q_1\rvert\lvert q_2\rvert}{r^2}$	$U = \frac{k_e q_1 q_2}{r}$	$k_e = 8.99\times 10^{9}\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}$
$v_{phase} = v_{crest} = \frac{\omega}{k}$	$p = \frac{h}{\lambda} = \hbar k$	$\Delta x\Delta p_x \geq \frac{\hbar}{2}$	$\Delta E\Delta t \geq \frac{\hbar}{2}$
$v_{group} = v_{packet} = \frac{d\omega}{dk}$	$\text{Probability} = \int_{x_1}^{x_2} P(x)\,dx$	$1 = \int_{-\infty}^{+\infty} P(x)\,dx$	$\langle f(x)\rangle = \int_{-\infty}^{+\infty} \psi^*(x)f(x)\psi(x)\,dx$
$\psi_n(x) = \sqrt{\frac{2}{L}}\sin\left(\frac{\pi n x}{L}\right)$	$E_n = \left(\frac{h^2}{8mL^2}\right)n^2$ for $n = 1, 2, \ldots$	$\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + U\right)\psi = E\psi$	$0 = \int_{-\infty}^{+\infty} \psi_m^*(x)\psi_n(x)\,dx$ if $m \neq n$
$\hat{p} = i\hbar\frac{d}{dx}$	$\hat{K} = \frac{\hat{p}^2}{2m}$	$\sigma_x = \sqrt{\langle x^2\rangle - \langle x\rangle^2}$	$\sigma_p = \sqrt{\langle\hat{p}^2\rangle - \langle\hat{p}\rangle^2}$
$\sigma_x\sigma_p \geq \hbar/2$	$\psi(x) = Ae^{ikx}$	$U(x) = \frac{1}{2}m\omega^2x^2$	$E_n = \left(n + \frac{1}{2}\right)\hbar\omega$ for $n = \mathbf{0}, 1, 2, \ldots$
$c = \frac{m\omega}{\hbar}$	$\psi_0 = \left(\frac{c}{\pi}\right)^{1/4} e^{-cx^2/2}$	$\psi_1 = \left(\frac{c}{\pi}\right)^{1/4}\sqrt{2c}\,xe^{-cx^2/2}$	$\psi_2 = \left(\frac{c}{\pi}\right)^{1/4}\frac{1}{\sqrt{2}}(2cx^2 - 1)e^{-cx^2/2}$
		$T \approx e^{-2\alpha L}$ where $E = \frac{\hbar^2k^2}{2m}$ & $\alpha = \sqrt{\frac{2m(U_0 - E)}{\hbar^2}}$	
$n = 1,2,3,\ldots$	$\ell = 0,1,2,\ldots,(n-1)$	$m_\ell = -\ell, -\ell+1, \ldots, 0, \ldots, \ell-1, \ell$	$m_s = \pm 1/2$
$L = \hbar\sqrt{\ell(\ell+1)}$	$L_z = m_\ell\hbar$	$S = \frac{\sqrt{3}}{2}\hbar$	$S_z = m_s\hbar$
$Radial\ p.d.f. = (\psi^*\psi)4\pi r^2$	$\psi_{100} = \frac{1}{\sqrt{\pi a_0^3}}e^{-r/a_0}$	$\psi_{200} = \frac{1}{4\sqrt{2\pi a_0^3}}\left(2 - \frac{r}{a_0}\right)e^{-r/2a_0}$	$\psi_{210} = \frac{1}{4\sqrt{\pi a_0^3}}\cdot\frac{r}{a_0}e^{-r/2a_0}\cos\theta$

$\text{P} = 10^{15}$	$\text{T} = 10^{12}$	$\text{G} = 10^{9}$	$\text{M} = 10^{6}$	$\text{k} = 10^{3}$	$\text{c} = 10^{-2}$	$\text{m} = 10^{-3}$	$\mu = 10^{-6}$	$\text{n} = 10^{-9}$	$\text{p} = 10^{-12}$	$\text{f} = 10^{-15}$	$\text{a} = 10^{-18}$

$\psi_{1\,0\,0} = \dfrac{1}{\sqrt{\pi a_0^3}} e^{-r/a_0}$	$\psi_{2\,0\,0} = \dfrac{1}{4\sqrt{2\pi a_0^3}} \left(2 - \dfrac{r}{a_0}\right) e^{-r/2a_0}$	$\psi_{3\,0\,0} = \dfrac{1}{81\sqrt{3\pi a_0^3}} \left[27 - 18\dfrac{r}{a_0} + 2\dfrac{r^2}{a_0^2}\right] e^{-r/3a_0}$
		$\psi_{3\,1\,0} = \dfrac{\sqrt{2}}{81\sqrt{\pi a_0^3}} \left[6\dfrac{r}{a_0} - \dfrac{r^2}{a_0^2}\right] e^{-r/3a_0} \cos\theta$
	$\psi_{2\,1\,0} = \dfrac{1}{4\sqrt{\pi a_0^3}} \cdot \dfrac{r}{a_0} e^{-r/2a_0} \cos\theta$	$\psi_{3\,1\,\pm 1} = \dfrac{1}{81\sqrt{\pi a_0^3}} \left[6\dfrac{r}{a_0} - \dfrac{r^2}{a_0^2}\right] e^{-r/3a_0} \sin\theta\, e^{\pm i\phi}$
		$\psi_{3\,2\,0} = \dfrac{1}{81\sqrt{6\pi a_0^3}} \cdot \dfrac{r^2}{a_0^2} e^{-r/3a_0} [3\cos^2\theta - 1]$
	$\psi_{2\,1\,\pm 1} = \dfrac{1}{8\sqrt{\pi a_0^3}} \cdot \dfrac{r}{a_0} e^{-r/2a_0} \sin\theta\, e^{\pm i\phi}$	$\psi_{3\,2\,\pm 1} = \dfrac{1}{81\sqrt{\pi a_0^3}} \cdot \dfrac{r^2}{a_0^2} e^{-r/3a_0} \sin\theta\cos\theta\, e^{\pm i\phi}$
		$\psi_{3\,2\,\pm 2} = \dfrac{1}{162\sqrt{\pi a_0^3}} \cdot \dfrac{r^2}{a_0^2} e^{-r/3a_0} \sin^2\theta\, e^{\pm i2\phi}$

$\int \sin^2 kx\ dx = \dfrac{x}{2} - \dfrac{\sin(2kx)}{4k} + C$	$\int \cos^2 kx\ dx = \dfrac{x}{2} + \dfrac{\sin(2kx)}{4k} + C$
$\int x\sin^2 kx\ dx = \dfrac{x^2}{4} - \dfrac{x\sin(2kx)}{4k} - \dfrac{\cos(2kx)}{8k^2} + C$	$\int x\cos^2 kx\ dx = \dfrac{x^2}{4} + \dfrac{x\sin(2kx)}{4k} + \dfrac{\cos(2kx)}{8k^2} + C$
$\int x^2\sin^2 kx\ dx = \dfrac{x^3}{6} - \dfrac{x^2\sin(2kx)}{4k} - \dfrac{x\cos(2kx)}{4k^2} + \dfrac{\sin(2kx)}{8k^3} + C$	$\int x^2\cos^2 kx\ dx = \dfrac{x^3}{6} + \dfrac{x^2\sin(2kx)}{4k} + \dfrac{x\cos(2kx)}{4k^2} - \dfrac{\sin(2kx)}{8k^3} + C$

The following integral table assumes a is real (not complex).	
$\int_{-\infty}^{+\infty} e^{-ax^2} = \sqrt{\dfrac{\pi}{a}}$	$\int e^{-ax}\, dx = -\dfrac{e^{-ax}}{a} + C$
$\int_{-\infty}^{+\infty} x^2\, e^{-ax^2} = \dfrac{1}{2} \cdot \sqrt{\dfrac{\pi}{a^3}}$	$\int xe^{-ax}\, dx = -\dfrac{e^{-ax}}{a^2}(ax + 1) + C$
$\int_{-\infty}^{+\infty} x^4\, e^{-ax^2} = \dfrac{3}{4} \cdot \sqrt{\dfrac{\pi}{a^5}}$	$\int x^2 e^{-ax}\, dx = -\dfrac{e^{-ax}}{a^3}(a^2x^2 + 2ax + 2) + C$
$\int_{-\infty}^{+\infty} x^6\, e^{-ax^2} = \dfrac{15}{8} \cdot \sqrt{\dfrac{\pi}{a^7}}$	$\int x^3 e^{-ax}\, dx = -\dfrac{e^{-ax}}{a^4}(a^3x^3 + 3a^2x^2 + 6ax + 6) + C$
$\int_{-\infty}^{+\infty} x^n\, e^{-ax^2} = 0$ if $n =$ odd integer	$\int x^4 e^{-ax}\, dx = -\dfrac{e^{-ax}}{a^5}(a^4x^4 + 4a^3x^3 + 12a^2x^2 + 24ax + 24) + C$

Name: ____

GO QUICKLY ON THIS PAGE. Sentence fragments are ok.

0a) Ignoring the pain of error analysis, what was the most interesting lab this semester? Briefly describe what was measured and why you found it interesting.

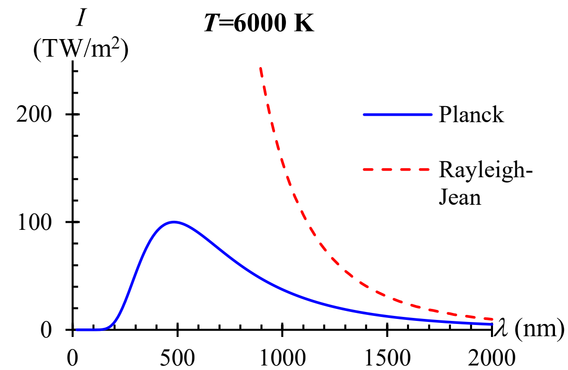
0b) During the entire semester we did a ton of math. In which **two** areas did your math abilities improve the most?

Algebra	Trig	Geometry	*Differential* calculus	*Integral* Calculus

0c) What are **two** life lessons or skills you hope to take from this semester after you transfer? It doesn't have to be something learned from me or the problem sets. It could be something you learned from a friend or something you discovered about yourself.

****0d) Describe a *conceptual* misunderstanding you were able to correct this semester.
Discuss the demo/concept you were confused about, what your misunderstanding was, and what the "correct" interpretation of the demo/concept is. Be brief (about 1 paragraph). **Include at least one labeled figure.**

We discussed plots of intensity versus wavelength similar to the figure shown at right. Notice one curve was generated using the Rayleigh-Jeans model while the other used the Planck model.



1a) Which of these models generates data which matches up well with experimental data at short wavelengths? Circle the best answer.

Rayleigh-Jean	Planck	Both	Impossible to determine without more info

**1b) Briefly explain what the phrase "the ultraviolet catastrophe" means to physicists. Use no more than three sentences.

**1c) Briefly explain Planck's hypothesis and why it is historically significant. I think 3 to 5 sentences should be enough.

A piece of freshly polished aluminum is placed inside a vacuum tube and illuminated with monochromatic light. A scientist observes the maximum speed of electrons ejected from the metal is $0.0125c$.

2a) **True or False:** It is reasonable to ignore special relativity for this problem. Write your answer in the box.

***2b) Determine the wavelength of light used.

2a	
2b	

A hydrogen atom initially in the $n = 6$ state changes to the $n = 8$ state.

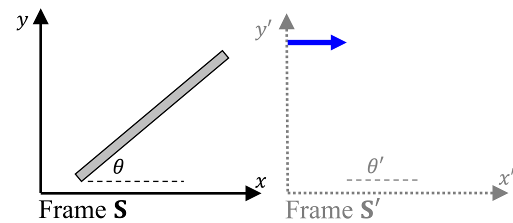
3a) What is the *initial* energy of the atom? **Answer in units of eV.**

3b) Did the atom absorb or emit a photon during this transition?
Write your answer in the box.

***3c) Determine momentum (magnitude) *of the photon* associated with this transition.
Write your answer in scientific notation with units of $\mathbf{kg \cdot \frac{m}{s}}$ **for full credit.**

3a	
3b	
3c	

Two observers measure the angle of a rod. In frame **S**, the rod's rest frame, observer 1 records rod length 2.50 cm and angle $\theta = 40.0°$. Observer 2 is in a spaceship travelling to the right at 64.0% of light speed (Frame **S′**). Figure not to scale.



4a) Which best describes the *length* of the rod observed by a scientist at rest relative to frame **S′**? Circle the best answer.

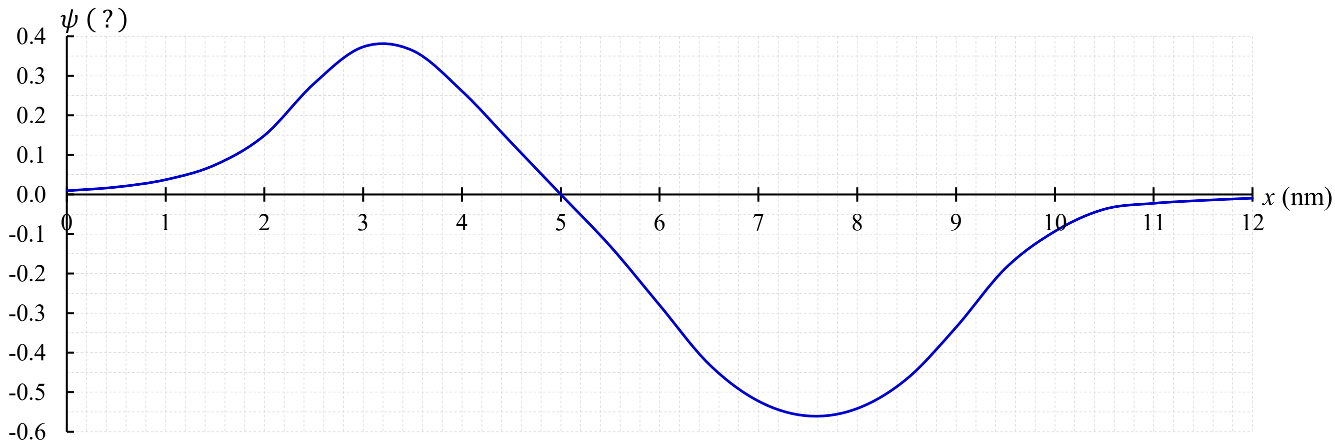
Same length	Longer	Shorter	Impossible to determine without more info

4a) Which best describes the *angle* (θ') of the rod observed frame **S′**? Circle the best answer.

$\theta = \theta'$	$\theta > \theta'$	$\theta < \theta'$	Impossible to determine without more info

****4c) Determine the rod length as measured by Observer 2.

4c	



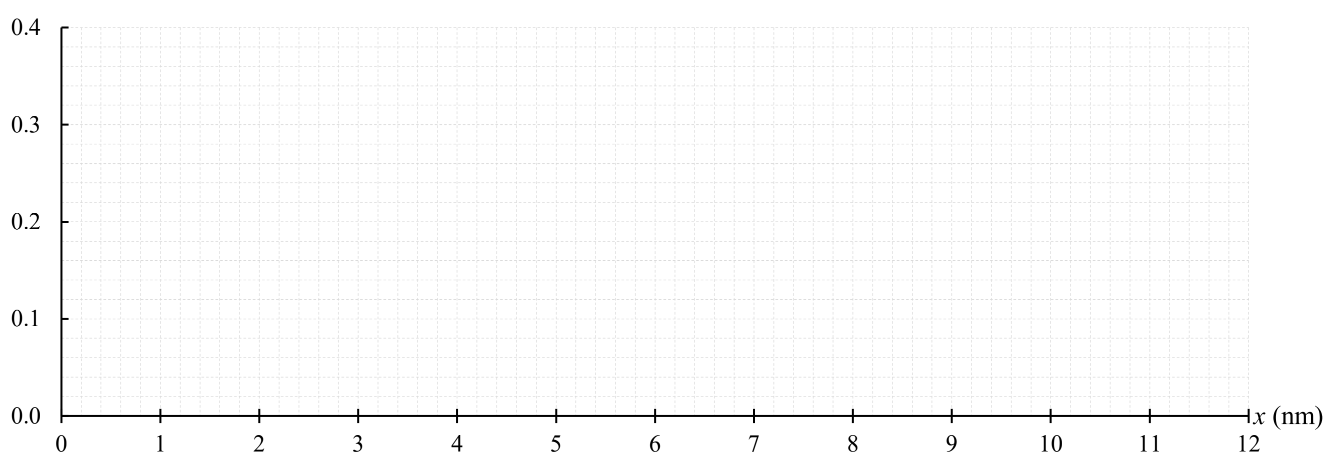
A normalized wavefunction for an electron trapped in a 1D asymmetric well is shown above.
You might want to do part 5d first…or at least double check parts a through c after doing part 5d.

5a) What units are appropriate for the variable ψ on the vertical axis?

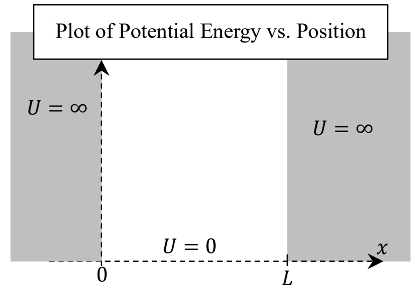
5b) For this question consider values of x strictly between 0 & 12 nm (do not include endpoints). At what position (or in which regions) does the electron have ZERO probability of being found?

5c) Where is the electron most likely to be found?

5d) Sketch a plausible curve for the probability distribution below. **Label the vertical axis with units!
I care about:1) peak locations, 2) peak heights, & 3) vertical axis label w/ units. I don't care about the exact curve *shape*.



A particle of mass m is confined to an infinite square well with potential shown by the figure at right. The particle is in the n^{th} energy level.
Notice $U = 0$ for $0 < x < L$ while $U = \infty$ elsewhere.



6a) What must be true about the value of ψ at position $x = L$? Circle the best answer.

$\psi(L) > +1$	$\psi(L) = +1$	$\psi(L)$ between $0 \& 1$	$\psi(L) = 0$
$\psi(L) < -1$	$\psi(L) = -1$	$\psi(L)$ between $-1 \& 0$	None of the other answers are correct.

6b) Which of the following is used for wavenumber k? Circle the best answer.

$k = \frac{2\pi L}{n}$	$k = \frac{2\pi n}{L}$	$k = \frac{\pi}{2nL}$	$k = \frac{\pi L}{2n}$	Impossible to determine without more info	None of the other answers are correct.

*****6c) Determine an algebraic expression for the expectation value of kinetic energy. Again, assume we are in the n^{th} energy level. Standard physics constants, $n, m, \& L$ may appear in your result.
Show work & put a box around your final result. Writing just the answer earns no points.

Assume a hydrogen atom in 3D has *radial* wave function

$$\psi(r) = Ae^{-9r/2L}$$

In this function assume L is a constant.

*****7a) Determine an algebraic expression for A which normalizes the wavefunction. **Show all work & put your final answer in the box.** Your final answer should include the parameter L.

7a	

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