SIGN HERE NOW:

1. The exam will last from 9:40 - 11:00 p.m. Use a #2 pencil to make entries on the answer sheet. Enter ID information items 2-5, now, on the answer sheet before the exam starts.
2. In the section labeled NAME (Last, First, M.I.) enter your last name, then fill in the empty circle for a blank, then enter your first name, another blank, and finally your middle initial.
3. Under STUDENT # enter your 9-digit RUID Number.
4. Enter 228 under COURSE; you may ignore the section number.
5. Under CODE enter the exam code from the label above.
6. During the exam, you may use pencils, a calculator, and one 8.5 x 11 inch sheet (both sides) with formulas and notes.
7. There are 16 multiple-choice questions on the exam. For each question, mark only one answer on the answer sheet. There is no deduction of points for an incorrect answer, so even if you cannot work out the answer to a question, you should make an educated guess. At the end of the exam, hand in the answer sheet and this SIGNED cover page. Retain the exam questions attached for future reference and study.
8. When you are asked to open the exam, make sure that your copy contains all 16 questions. Raise your hand if this is not the case, and a proctor will help you. Also raise your hand during the exam if you have a question.
9. Please have your student ID ready to show to the proctor during the exam.
Possibly useful information:

1) Speed of light in vacuum is \( c = 3.00 \times 10^8 \) m/s.
2) 1 eV = 1.60 \times 10^{-19} \) J.
3) J = kg \cdot m^2/s^2.
4) Wien’s displacement law constant is 2.90 \times 10^{-3} \) m \cdot K.
5) Rydberg constant is \( R = 1.10 \times 10^7 \) m\(^{-1}\).
6) \( h \cdot c \cdot R = 13.60 \) eV.
7) \( \hbar = h/2\pi \).
8) Photon mass is 0.
9) Metric prefixes: 1 G = 10^9, 1 M = 10^6, 1 k = 10^3, 1 m = 10^{-3}, 1 \mu = 10^{-6},
and 1 n = 10^{-9}.
10) Planck constant is \( h = 6.63 \times 10^{-34} \) J \cdot s = 4.14 \times 10^{-15} \) eV \cdot s.
11) Electron rest mass is 10^{-30} kg.
12) Proton rest energy is 938 MeV.
13) Bohr radius is 0.5 \times 10^{-10} \) m.
1. Using the Heisenberg uncertainty principle, estimate the electron kinetic energy in a one-dimensional square well with width two times the Hydrogen atom Bohr radius. Choose the closest answer.
   
a) \( 1 \mu\text{eV} \)
   b) \( 1 \text{meV} \)
   c) \( 1 \text{eV} \)
   d) \( 100 \text{eV} \)
   e) \( 1 \text{keV} \)

2. A photon of blue light has a wavelength of 473 nm. What is the photon’s momentum?
   
a) zero, because photon mass is zero
   b) \( 1.4 \times 10^{-31} \text{kgm/s} \)
   c) \( 9 \times 10^{-31} \text{kgm/s} \)
   d) \( 1.6 \times 10^{-31} \text{kgm/s} \)
   e) \( 3 \times 10^{-31} \text{kgm/s} \)

3. An object, which at rest has a shape of a perfect sphere with a diameter 1 m, is flying past an observer with a relativistic speed. Determine the speed of the object, if it appears to be squashed by 50 \( \mu \text{m} \) in the direction of motion.
   
a) \( 0.99c \)
   b) \( 0.50c \)
   c) \( 0.87c \)
   d) \( 1.11c \)
   e) \( 0.01c \)

4. An alien spaceship approaching the Earth with a speed of 0.4c fires a missile towards the Earth. The speed of the missile with respect to the ship is 0.6c. Find the speed of the missile relative to the Earth.
   
a) \( 0.2c \)
   b) \( 0.26c \)
   c) \( 0.6c \)
   d) \( 0.8c \)
   e) \( c \)
5. Find the wavelength of light necessary to produce electrons with maximum kinetic energy of 1 eV in a photoelectric effect experiment with gold. The work function of gold is 5 eV.

\[
\begin{align*}
\text{a) } & 248 \text{ nm} \\
\text{b) } & 206 \text{ nm} \\
\text{c) } & 500 \text{ nm} \\
\text{d) } & 1.24 \mu \text{m} \\
\text{e) } & 2.48 \mu \text{m}
\end{align*}
\]

6. What is the speed of a relativistic proton whose kinetic energy is 145.1 MeV?

\[
\begin{align*}
\text{a) } & 0 \\
\text{b) } & 0.25c \\
\text{c) } & 0.50c \\
\text{d) } & 0.75c \\
\text{e) } & c
\end{align*}
\]

7. A non-relativistic electron moving as a free particle in one dimension (that is, \(U(x) = 0\)) has a kinetic energy \(E\). The electron can be described by the wave function: \(\psi(x) = A_1 e^{ikx} + A_2 e^{-ikx}\). What is the wavenumber of the electron, \(k\)?

\[
\begin{align*}
\text{a) } & \frac{(2mE)^{0.5}}{\hbar} \\
\text{b) } & \frac{(mE)^{0.5}}{2\hbar} \\
\text{c) } & \frac{(2mE)^2}{\hbar} \\
\text{d) } & E/\hbar \\
\text{e) } & 2\pi\hbar/(2mE)^{0.5}
\end{align*}
\]

8. What is the energy of the first excited state \((n = 2)\) of a singly ionized He atom?

\[
\begin{align*}
\text{a) } & 3.4 \text{ eV} \\
\text{b) } & -3.4 \text{ eV} \\
\text{c) } & 13.6 \text{ eV} \\
\text{d) } & -13.6 \text{ eV} \\
\text{e) } & -54.4 \text{ eV}
\end{align*}
\]
9. The speed of a relativistic electron doubles. What happens to its momentum?
   a) Momentum also doubles.
   b) It remains the same, because momentum should be conserved.
   c) It increases more than by a factor of two.
   d) It decreases by a factor of two.
   e) It increases, but less than by a factor of two, because the electron will radiate electromagnetic energy.

10. A photon, an electron and a proton have the same wavelength. Which has the smallest momentum?
    a) The electron
    b) The proton
    c) The photon
    d) All have the same momentum
    e) The electron and the proton

11. The temperature of a blackbody doubles. How does the peak wavelength of its emission $\lambda_{max}$ change?
    a) Stays the same
    b) Doubles
    c) Increases by a factor of 16
    d) Decreases by a factor of 4
    e) Decreases by a factor of 2

12. An electron in a one-dimensional infinite square potential well of width 1 nm is excited from the ground state ($n = 1$) to the first excited state ($n = 2$) by absorbing a photon. What is the photon energy?
    a) 1.02 eV
    b) 13.6 eV
    c) 10.2 eV
    d) 100 eV
    e) $16.3 \times 10^{-20}$ eV

13. An electron in an infinite square potential well of width $a$ is in the state with $n = 3$. Determine the probability to find the electron in the range $x = a/3$ to $2a/3$.
    a) 0
    b) 1/4
    c) 1/3
    d) 1/2
    e) 2/3

   The wave functions look like: The $n=3$ probability looks like:

   You can see from the symmetry that
   $P(\frac{a}{3} < x < \frac{2a}{3}) = \frac{1}{3}$
14. A transition from the \( n = 3 \) state to the \( n = 2 \) state of a harmonic oscillator is accompanied by emission of a photon with energy 5 eV. What is the ground state energy of this harmonic oscillator?

\[ E_{\text{HO}} = \left(n + \frac{1}{2}\right) \hbar \omega \]

\( \text{b) } 2.5 \text{ eV} \)

\( \text{c) } 1.9 \text{ eV} \)

\( \text{d) } -13.6 \text{ eV} \)

\( \text{e) } 136 \text{ eV} \)

So

\[ E_g = E_{n=3} - E_{n=2} = \left(3 + \frac{1}{2}\right) \hbar \omega - \left(2 + \frac{1}{2}\right) \hbar \omega = \frac{1}{2} \hbar \omega = 2.5 \text{ eV} \]

15. A hydrogen atom undergoes a transition from an excited state \( (n = 3) \) to the ground state \( (n = 1) \) and emits a photon. Determine the wavelength of the photon.

\( \text{a) } 102 \text{ nm} \)

\( \text{b) } 120 \text{ nm} \)

\( \text{c) } 60 \text{ nm} \)

\( \text{d) } 220 \text{ nm} \)

\( \text{e) } 473 \text{ nm} \)

To obtain: \( \lambda = \frac{\hbar c}{E_g} \)

16. X-rays undergo Compton scattering off free electrons. Observation at a certain angle with respect to the incident beam shows that the wavelength of the scattered X-rays increases by 0.0022 nm. Find the angle of observation.

\( \text{a) } 0^\circ \)

\( \text{b) } 45^\circ \)

\( \text{c) } 60^\circ \)

\( \text{d) } 90^\circ \)

\( \text{e) } 180^\circ \)

\[ \lambda' - \lambda = \frac{(h/m_e c)(1 - \cos \theta)}{\text{given constants}} = \text{find this} \]

\[ 0.0022 \text{ nm} \]

\[ \frac{\lambda}{\text{previous}} = \frac{6.6 \times 10^{-34}}{10^{-30} \times 3 \times 10^8} = 2.2 \times 10^{-12} \text{ m} \]

\[ = 0.0022 \text{ nm} \]

Thus

\[ 1 - \cos \theta = \frac{2}{1} \]

\[ \cos \theta = 0 \]

\[ \theta = 90^\circ \]