1. The exam will last from 3:35pm to 4:30pm. Use a #2 pencil to make entries on the answer sheet. Enter the following id information now, before the exam starts.

2. In the section labelled NAME, 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 Student ID Number. Under COURSE enter 273.

4. During the exam, you may use pencils, a calculator, and ONE $8\frac{1}{2}'' \times 11''$ sheet of paper with formulas and notes.

5. There are 16 multiple-choice questions on the exam. For each question, mark only one answer on the answer sheet. There is no subtraction 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 only the answer sheet. Retain this question paper for future reference and study.

6. Useful numerical constants are given on the next page. Before starting the exam, make sure that your copy contains the page of constants and all 16 questions. Bring your exam to the proctor if this is not the case.
Elementary charge $e = 1.6 \times 10^{-19} \, C$

1 electron volt $(eV) = 1.6 \times 10^{-19} \, J$

Speed of light $c = 3 \times 10^8 \, m/s$

Planck's constant $\hbar = 6.63 \times 10^{-34} \, J \cdot s = 1240 \, nm \cdot eV/c$

$h = \hbar/2\pi$

Compton wavelength of electron $h/mc = 0.0024 \, nm$

Ground-state energy of hydrogen $= -13.6 \, eV$

Rydberg constant $R = 0.0109678 \, nm^{-1}$

Avogadro's number $= 6.02 \times 10^{23} \, \text{molecules/mole}$

Electron mass $= 9.11 \times 10^{-31} \, kg = 0.511 \, MeV/c^2$

Proton mass $= 1.673 \times 10^{-27} \, kg = 938.3 \, MeV/c^2$

Neutron mass $= 1.675 \times 10^{-27} \, kg = 939.6 \, MeV/c^2$

Atomic mass unit $1 \, u = 931.5 \, MeV/c^2$

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1. Imagine for a moment that the speed of light is only 1000 miles per hour (mph). How would the age of a passenger flying from Newark NJ to Chicago IL (a distance of 720 miles) in a Boeing 737 (at a cruising speed of 500 mph) differ from that of his twin who stayed at home?
   a) Passenger would be the same age.
   b) Passenger would be 11.6 minutes older.
   c) Passenger would be 11.6 minutes younger.
   d) Passenger would be 21.6 minutes younger.
   e) There is not enough information to tell.

\[
\Delta T = \frac{d}{v - \frac{d}{c^2}} = \frac{1200}{500 - \frac{1200}{1000}} = 1.44 \text{ hr}
\]

\[
y = (1 - \frac{v^2}{c^2})^{-\frac{1}{2}} = (1 - \frac{500^2}{1000^2})^{-\frac{1}{2}} = 1.15
\]

\[
\Delta T = 1.44 \text{ hr} = 1.16 \text{ min}
\]

2. The mass of the muon is 106 MeV/c². What would the ionization energy of the Hydrogen atom be if the electron were replaced by a muon?
   a) 0.066 eV
   b) 13.6 eV
   c) 2.82 keV
   d) 6.8 eV
   e) 1. keV

\[
E = \frac{m_e c^2}{2} = \frac{m_e}{m_e + 13.6 \text{ eV}} = \frac{106}{0.311} = 339.2 \text{ keV}
\]

3. Hydrogen is a bound state of an electron and a proton. Positronium is a bound state of an electron and a positron. What is the ionization energy of Positronium?
   a) 0.066 eV
   b) 13.6 eV
   c) 27.2 eV
   d) 6.8 eV
   e) 1. keV

\[
E_{\text{ionization}} = \frac{m_e c^2}{2m_e} = 13.6 \text{ eV}/2 = 6.8 \text{ eV}
\]

4. A distant planet is approximately 350 light years away from Earth, in the Earth’s reference frame. If a spaceship were to travel at constant velocity, at least how fast would it need to travel so that its occupants could live long enough to get to the end of their journey? Assume that the occupants have at most 70 years left of their life when they start their trip.
   a) At least 0.95c
   b) At least 0.96c
   c) At least 0.97c
   d) At least 0.98c
   e) At least 0.99c

\[
y = (1 - 0.98^2)^{-\frac{1}{2}} = 5.03
\]

\[
s = \frac{c}{v} = \frac{350}{0.98} = 5, \text{ so a gamma factor of at least 5 is needed.}
\]
5. According to earth observers, a cosmic-ray hitting the atmosphere creates a pion moving at 0.91c, which then travels 20 m before decaying. How long did the pion live according to measurements in the pion's rest frame?

\[
\frac{d}{dt} = \frac{d}{v} \cdot \gamma = \frac{2.0 \text{ m}}{0.81 \cdot \gamma \cdot 10 \text{ m/s}} = 0.123 \text{ ms}
\]

- a) 0.022 \text{ ms}
- b) 0.030 \text{ ms}
- c) 0.073 \text{ ms}
- d) 0.133 \text{ ms}
- e) 0.243 \text{ ms}

6. Relative to the earth, rocket A moves East at 0.50c, and rocket B moves North at 0.75c. What is the speed of rocket B as measured by observers in rocket A?

\[
\begin{align*}
U_x &= \frac{1}{\gamma} \frac{U_x - U^2}{1 - v \cdot U_x / c^2} = \frac{-0.5c}{1 - 0.5} = -0.65c \\
U_y &= \frac{1}{\gamma} \frac{U_y}{1 - v \cdot U_x / c^2} = \frac{0.75c}{1.15 (1 - 0.5)} = 0.65c \\
U &= \sqrt{U_x^2 + U_y^2} = 0.82c
\end{align*}
\]

- a) About 0.49c
- b) About 0.70c
- c) About 0.65c
- d) About 0.82c
- e) About 0.90c

7. Light of wavelength \( \lambda = 400 \text{ nm} \) shines on a certain metal. The resulting photocurrent is stopped by a stopping potential of 2.5 Volts. What wavelength of light would require doubling the stopping voltage?

\[
\frac{h \lambda}{\lambda} - k \cdot \varphi = \frac{1240}{5.6} \Rightarrow \lambda = \frac{1240}{5.6} = 221 \text{ nm}
\]

- a) \( \lambda = 221 \text{ nm} \)
- b) \( \lambda = 44 \text{ nm} \)
- c) \( \lambda = 166 \text{ nm} \)
- d) \( \lambda = 633 \text{ nm} \)
- e) Not enough information given.

8. A beam of light is emitted at an angle of 30° with respect to the x-axis in the rest frame. Another inertial frame moving along the x-axis in the positive direction observes that the angle is 90°. What is the velocity of the frame?

\[
\begin{align*}
U_x' = c \cdot \cos \theta \\
U_y' = \frac{U_x - v}{1 - v \cdot U_x / c^2}
\end{align*}
\]

- a) About 0.87c
- b) About 0.90c
- c) About 0.94c
- d) About 1.0c
- e) It is impossible
9. A spaceship moves radially away from Earth. How fast is it going when sodium streetlamps ($\lambda = 589$ nm) on Earth first become invisible to human eyes on the ship? The human eye can see wavelengths from 400 to 700 nm.

a) 0.086 c
b) 0.170 c
c) 0.253 c
d) 0.339 c
e) 0.369 c

10. If a particle’s kinetic energy equals its rest energy, what is its speed?

a) About 0.25c
b) About 0.50c
c) About 0.67c
d) About 0.75c
e) About 0.87c

11. A particle of mass 1200 MeV/c^2 is at rest. It spontaneously breaks into three fragments, all of equal mass, but traveling at 0.9c, 0.8c, and 0.5c. What is the mass of the fragments? (Note that “mass” means “rest mass”).

a) 174 MeV/c^2
b) 234 MeV/c^2
c) 278 MeV/c^2
d) 324 MeV/c^2
e) 364 MeV/c^2

12. A photoelectric effect experiment is done using light of some wavelength $\lambda$. The photoelectrons are observed to have a maximum kinetic energy of 5 eV. If the experiment is repeated using light of wavelength $2\lambda$ on the same metal, it is found that the maximum electron kinetic energy is 2 eV. What is the work function of the metal?

a) 1 eV
b) 2 eV
c) 3 eV
d) 4 eV
e) 5 eV

\[
\frac{h}{\lambda} = 5 + \varphi \Rightarrow \frac{h}{2\lambda} = 2 + \varphi \Rightarrow \frac{h}{\lambda} = 4 + 2\varphi
\]

\[
\therefore \quad 4 + 2\varphi = 5 + \varphi \Rightarrow \varphi = 1
\]
13. The H_α line has a wavelength of 656.1 nm. What is its wavelength when emitted from a star receding with a speed of 3000 km/s?

a) About 593 nm  

b) About 626 nm  

c) About 649 nm  

d) About 663 nm  

e) About 725 nm

\[ \lambda = \frac{c}{v} \sqrt{1 - \beta^2} \Rightarrow \lambda = \lambda_0 \sqrt{1 - \beta^2} \]

\[ \lambda_0 = 656.1 \text{ nm}, \beta = 0.01, \text{ so } \lambda = 663 \text{ nm} \]

14. A space traveler moving at a speed of 0.7c with respect to the earth makes a trip to a distant star that is stationary relative to the earth. She measures the length of the trip to be 6.5 light-years. What would be the length of this trip (in light-years) as measured by a traveler moving at a speed of 0.9c with respect to the earth?

a) 6.5 light-years  

b) 9.1 light-years  

c) 5.6 light-years  

d) 4.0 light-years  

e) 20.8 light-years

\[ \gamma_l = \left(1 - (0.7^2)\right)^{-1/2} = 1.40 \]

\[ \gamma_l = \left(1 - (0.9^2)\right)^{-1/2} = 2.29 \]

\[ L = 6.5 \cdot \gamma_l \]

15. An electron is moving so fast that it has a total energy that is five times its rest energy. What is its kinetic energy?

a) 0.511 MeV  

b) 0.612 MeV  

c) 2.04 MeV  

d) 2.56 MeV  

e) 3.07 MeV

\[ E = K + mc^2 \]

\[ E = 5mc^2 \Rightarrow K = E - mc^2 = 4 \times 0.511 \text{ MeV} = 2.04 \text{ MeV} \]

16. Electrons at rest are hit by incident photons. The maximum kinetic energy given to an electron is 30 keV. What is the wavelength of the incident light?

a) 0.0243 nm  

b) 0.0486 nm  

c) 0.030 nm  

d) 0.012 nm  

e) None of the other answers

\[ \frac{\hbar}{\hbar c} = \left( \frac{\lambda - \lambda_0}{\lambda_0} \right) \]

\[ \text{Compton eq.: } \lambda' = \lambda - \frac{\hbar}{mc} \left(1 - \cos \theta \right) \]

\[ \text{Here } \theta = 90, \text{ so } \lambda' = \lambda + \frac{\hbar}{mc} \text{. Plug in to } \lambda \text{ and you get:} \]

\[ \frac{\hbar}{\hbar c} = \left( \frac{\lambda - \lambda_0}{\lambda} \right) \]

\[ \text{Plugging in for } K, h, e, m, \text{ gives: } 2.42 = \left( \frac{\lambda - \lambda_0}{\lambda + 0.7 \cdot 18} \right) \]

\[ \text{This is satisfied by } \lambda = 0.012 \text{ nm} \]