Allowed: One sheet of notes, pencils, scratch paper, calculator, ruler. No time limit.

The first part of this exam consists of multiple choice questions. Each multiple choice problem is worth 4 points. The second part consists of worked problems. For these problems you will need to show your work to receive credit. Each of the worked problems is worth 9 points.

Do not write on this exam! Answers to the multiple choice problems should be recorded on your bubble sheet. Your work and answers to the worked problems should be done on your “Worked Problem Answer Sheet.” Put your correct CID on the Worked Problem Answer Sheet or you will lose 5 points! Do not staple more than three sheets of paper to your answer sheet, and make sure they are stapled well and aligned with the answer sheet, or you will lose up to 5 points!

Unless otherwise indicated, for multiple choice questions with numerical answers, the choices represent the answer rounded to three significant figures.

To receive full credit on the worked problems section, please show all work clearly and write neatly. If you wish to get partial credit on problems with incorrect answers, be sure to solve all questions algebraically first, then plug in numbers (with units) to get the final answer. Unless otherwise instructed, give all numerical answers to three significant digits in SI units.

Remember to keep extra digits in intermediate results, otherwise your final answer may be off. Also, check that your results make sense and have correct units. You can also consider what happens when you set a variable to a value that gives you a known result.

Do not do work for one problem in space allotted for another problem.

List of Elements

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Possibly Useful Information

- Speed of Light in Vacuum: $c = 2.9979 \times 10^8$ cm/s
- Planck's Constant: $h = 6.6261 \times 10^{-34}$ J·s
- Compton Wavelength: $\lambda_C = 2.43 \times 10^{-3}$ nm
- Rydberg Constant: $R_H = 1.0974 \times 10^7$ m$^{-1}$
- Electron-Volt: $1$ eV $= 1.6022 \times 10^{-19}$ J
- Mass of an Electron: $m_e = 9.1094 \times 10^{-31}$ kg
- Mass of a Proton: $m_p = 1.6726 \times 10^{-27}$ kg
- Mass of a Neutron: $m_n = 1.6749 \times 10^{-27}$ kg
- Mass of a Carbon-12 Atom: $m_C = 1.9926 \times 10^{-26}$ kg

Multiple Choice

1. I stomp my foot twice. I measure a time of 5.69 seconds passing between the first and second time I stomp my foot. If someone was flying past in a spaceship at a speed of 0.911 times the speed of light, what time would they measure between the two times I stomp my foot?

   (a) 19.1 s
   (b) 4.21 s
   (c) 2.35 s
   (d) $13.8 \times 10^{-3}$ s
   (e) 1.7 s
   (f) None of the above

2. If a neutron has a rest energy of 939.57 MeV, how much energy must I give a neutron at rest to accelerate it to 0.85 times the speed of light?

   (a) $1.78 \times 10^3$ MeV
   (b) 799 MeV
   (c) $3.39 \times 10^3$ MeV
   (d) $844 \text{ MeV}$
   (e) $2.45 \times 10^3$ MeV
   (f) 495 MeV
   (g) None of the above

3. The isotope $^{240}_{95}$Am undergoes alpha decay with a half-life of 50.8 h. If a sample of $^{240}_{95}$Am is emitting $3.04 \times 10^3$ alpha particles per minute at some particular time, at what rate will it be emitting alpha particles 172 h later?

   (a) 103 per minute
   (b) $3.18 \times 10^4$ per minute
   (c) $3.00 \times 10^3$ per minute
   (d) $1.52 \times 10^3$ per minute
   (e) $291 \text{ per minute}$
   (f) $2.26 \times 10^3$ per minute
   (g) None of the above

4. I’m not saying that $^{29}_{14}$Si actually exists, or that if it does it decays via beta minus decay emitting an electron. But, if it does, or did, what would it become once it had decayed?

   (a) $^{30}_{14}$P
   (b) $^{29}_{13}$Al
   (c) $^{30}_{16}$S
   (d) $^{29}_{12}$Mg
   (e) $^{28}_{12}$Mg
   (f) None of the above

5. I shine a beam of light with a wavelength of 406 nm at a metal with a work function of 1.37 eV. What will the kinetic energy of the ejected electrons be?

   (a) $5.03 \times 10^5$ eV
   (b) $1.37 \text{ eV}$
   (c) $1.22 \times 10^1$ eV
   (d) $1.68 \text{ eV}$
   (e) 3.05 eV
   (f) $1.93 \times 10^{-17}$ eV
   (g) None of the above

6. A photon with a wavelength of $1.02 \times 10^{-2}$ nm undergoes Compton scattering off of an electron, being scattered back 180 degrees. What is the wavelength of the photon after it has been scattered?

   (a) $1.51 \times 10^{-2}$ nm
   (b) 4.86 nm
   (c) $4.86 \times 10^{-3}$ nm
   (d) $2.43 \times 10^{-3}$ nm
   (e) $1.02 \times 10^{-2}$ nm
   (f) $1.26 \times 10^{-2}$ nm
   (g) None of the above

7. I’m just making things up here . . . but assuming that the reaction can occur, what is $x$ in the fission reaction below?

   $^{247}_{112}$Cp + $n$ $\rightarrow$ $^{88}_{41}$Nb + $^{71}_{29}$Lu + $4n$

   (a) 247
   (b) 87
   (c) 88
8. A duck flies past me at a speed of $0.617c$. If the length of the duck, as measured by someone in a reference frame at rest with respect to the duck, is 0.713 meters, what will I measure the length of the duck to be?

(a) 0.442 m  
(b) 0.441 m  
(c) 0.906 m  
(d) 1.15 m  
(e) 0.561 m  
(f) None of the above

9. If a proton and an anti-proton (each with a mass of $1.6726 \times 10^{-27} \text{kg}$) annihilate, converting the rest energy of the two particles into a pair of photons, what will the wavelength of the photons be? Assume that energy is shared equally between the photons.

(a) $1.19 \times 10^{-7} \text{ m}$  
(b) $1.32 \times 10^{-15} \text{ m}$  
(c) $8.25 \times 10^{12} \text{ m}$  
(d) $1.32 \times 10^{-6} \text{ m}$  
(e) $8.25 \times 10^{3} \text{ m}$  
(f) $1.50 \times 10^{-10} \text{ m}$  
(g) None of the above

10. The quantum uncertainty of the position of a quarter with a mass of 5.67 kg is $6.25 \times 10^{-7} \text{ m}$. What is the minimum uncertainty in the momentum of the quarter?

(a) $1.58 \times 10^{8} \text{ kg m/s}^2$  
(b) $0.527 \text{ kg m/s}^2$  
(c) $5.30 \times 10^{-28} \text{ kg m/s}^2$  
(d) $2.65 \times 10^{-28} \text{ kg m/s}^2$  
(e) $8.44 \times 10^{-29} \text{ kg m/s}^2$  
(f) $1.19 \times 10^{28} \text{ kg m/s}^2$  
(g) None of the above

11. What is the de Broglie wavelength of a 3.00 $\times 10^{-3} \text{ kg}$ pencil traveling at a velocity of 15.2 m/s?

(a) $3.02 \times 10^{-35} \text{ m}$  
(b) $1.45 \times 10^{-32} \text{ m}$  
(c) 21.9 m

12. The Aluminum Falcon flies past the Eyring Science Center at a velocity of $0.728c$ in the $x$ direction. As it is doing so it shoots a flying monkey which travels at a speed of $0.326c$ in the $x$ direction as measured by someone on board the Aluminum Falcon. How fast is the flying monkey moving as measured by someone at rest with respect to the Eyring Science Center?

(a) $0.527c$  
(b) $1.38c$  
(c) $1.05c$  
(d) $0.325c$  
(e) $1.54c$  
(f) $0.586c$  
(g) None of the above

13. I’m not saying that $^{52}\text{Mn}$ actually exists, or that if it does it decays via alpha decay. But, if it does, or did, what would it become once it had decayed?

(a) $^{48}\text{V}$  
(b) $^{52}\text{Co}$  
(c) $^{52}\text{Fe}$  
(d) $^{52}\text{Cr}$  
(e) $^{52}\text{Fe}$  
(f) None of the above

14. What is the energy of a photon with a wavelength of 669 nm?

(a) $1.33 \times 10^{-31} \text{ eV}$  
(b) $8.29 \times 10^{5} \text{ eV}$  
(c) $1.85 \text{ eV}$  
(d) $4.43 \times 10^{-40} \text{ eV}$  
(e) $2.01 \times 10^{11} \text{ eV}$  
(f) $3.21 \times 10^{-17} \text{ eV}$  
(g) None of the above

15. A space probe flies past the Earth at a speed of 0.906c. Precisely 137 seconds after passing the Earth, as measured by a clock on board the probe, the probe shoots a laser signal back to the Earth. As measured by someone on the Earth, how long is the interval of time between when the probe passed the Earth and the time when the laser light from the probe reaches the Earth?

(a) 52.5 s
(b) 617 s
(c) 261 s
(d) 293 s
(e) 124 s
(f) None of the above

16. At what speed is an electron’s kinetic energy equal to 3.09 times its rest energy?

17. A hydrogen atom is in the \( n = 3 \) state. Then it absorbs a photon with a wavelength of \( 1.87 \times 10^3 \) nm. What state is it in now (i.e., what is \( n \) now)?

18. You drop a ball with a mass of 2.36 kg off of a cliff. Neglecting things like air friction, and assuming an acceleration of gravity of 9.8 m/s\(^2\), what is the de Broglie wavelength of the ball after it has fallen 2.64 meters?

19. You’ve heard of Schrödinger’s cat, right? Let’s imagine that Mr. Schrödinger puts his cat into a box with a poison gas death bomb primed to go off when a particular \(^{240}\)Am nucleus decays. This nuclide decays via alpha decay with a half-life of 50.8 hours. If Schrödinger puts the cat in the box and leaves it there for 21.8 hours, what is the probability that, when he opens the box, he will find that the poison gas death bomb has gone off?

20. You throw a ball really hard, so that it travels at a velocity of 0.533 \( c \) with respect to the Earth. A moment later, your loyal dog runs after it. How fast will your dog have to run such that, in your dog’s reference frame, the ball will be approaching the dog at a rate of 0.471 \( c \)?

Free Response

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Solutions

17. The photon has an energy of

\[ E = hf = \frac{hc}{\lambda} \]

The change in energy of the atom is

\[ E = E_0 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

Those two should be the same. Setting them equal and solving for \( n_f \), we get

\[ \frac{hc}{\lambda} = E_0 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

\[ \frac{1}{n_f^2} = \frac{1}{n_i^2} + \frac{hc}{\lambda E_0} \]

\[ n_f^2 = \left( \frac{1}{n_i^2} + \frac{hc}{\lambda E_0} \right)^{-1} \]

\[ n_f = \left( \frac{1}{n_i^2} + \frac{hc}{\lambda E_0} \right)^{-1/2} \]

\[ n_f = \left( \frac{1}{3^2} + \frac{(1239.8) \text{ eV} \cdot \text{nm}}{1.87 \times 10^3 \text{ nm} \cdot (-13.606) \text{ eV}} \right)^{-1/2} = 4 \]

18. The de Broglie wavelength is given by

\[ \lambda_{DB} = \frac{h}{p} \]

This problem doesn’t involve relativistic speeds, so I can use classical energy and momentum relations. So

\[ \lambda_{DB} = \frac{h}{mv} \]

We are given \( m \). To find \( v \), note that after falling a distance of \( L \), the ball will have a kinetic energy of

\[ \frac{1}{2}mv^2 = mgL \]

So

\[ v = \sqrt{2gL} \]

and

\[ \lambda_{DB} = \frac{h}{m\sqrt{2gL}} = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{2.36 \text{ kg} \cdot 9.8 \text{ m/s}^2 \cdot 2.64 \text{ m}} \]

\[ \lambda_{DB} = 3.90 \times 10^{-35} \text{ meters} \]

19. Decay is probabilistic. If I had a buzzillion nuclei, I know that 1/2 of them would decay in a half-life. That means that for any given nuclei, there is a 50%

Since the number of atoms remaining in a sample after a given time is given by

\[ N = N_0 e^{-\lambda t} \]

the probability of any given nuclei still being around is

\[ P_{\text{still here}} = e^{-\lambda t} \]
The probability that it has decayed, then, is

\[ P_{\text{decayed}} = 1 - P_{\text{still here}} = 1 - e^{-\lambda t} \]

\[ P_{\text{decayed}} = 1 - e^{-\ln(2)t/T_{1/2}} = 1 - e^{-\ln(2)21.8/50.8} \]

\[ P_{\text{decayed}} = 0.257 \text{ or } 25.7\% \]

20. We need to find the velocity of the dog’s frame \( v \). We know that the speed of the ball in your frame is

\[ u_x = 0.533c \]

In the dog’s frame, the ball is moving in the other direction, such that

\[ u'_x = -0.471c \]

Using the Lorentz velocity transformation, we get

\[ u_x = \frac{u'_x + v}{1 + u'_x v/c^2} \Rightarrow \]

\[ u_x(1 + u'_x v/c^2) = u'_x + v \]

\[ u_x + u_x u'_x v/c^2 = u'_x + v \]

\[ u_x u'_x c^2 - v = u'_x - u_x \]

\[ v(u_x u'_x c^2 - 1) = u'_x - u_x \]

\[ v = \frac{u'_x - u_x}{u_x u'_x c^2 - 1} \]

\[ v = \frac{-0.471c - 0.533c}{0.533 \cdot (-0.471) - 1} \]

\[ v = 0.803c \]