\[
B = \left(\frac{2}{3}m_H + Nm_n - M_C\right)c^2
\]

1. What is the average binding energy per nucleon for \(\frac{4}{5}C\), whose atomic mass is 13.003355 u? (See the page of constants for other relevant masses)

   a) 7.23 MeV
   b) 7.47 MeV
   c) 7.71 MeV
   d) 64.8 MeV
   e) 787 MeV

\[
B = (6 \times 1303000 \text{ MeV}) + (2 \times 1.008665) - 13.003355 = 9.71 \text{ MeV}
\]

\[
B = \frac{9.71}{13} = 7.47 \text{ MeV}
\]

2. Which of the following statements about the strong nuclear force is false?
   a) It causes radioactivity to occur.
   b) It is much stronger than the gravitational force between two nucleons separated by about 1 fm.
   c) It is much stronger than the electrical force between two nucleons separated by about 1 fm.
   d) It is charge-independent.
   e) It is short-range.

3. What is the ratio of the nuclear volume of \(^{207}\text{Pb}\) to that of \(^{24}\text{Mg}\)?

   a) About 6.8
   b) About 1.0
   c) About 8.6
   d) About 1.9
   e) About 2.1

\[
\frac{V_{\text{Pb}}}{V_{\text{Mg}}} = \frac{207}{24} = 8.6
\]

4. For a certain radioactive substance, it is found that 25% of the nuclei decay in 3.0 hours. What is the half-life of the substance?

   a) About 12 hours
   b) About 7.2 hours
   c) About 0.75 hours
   d) About 1.5 hours
   e) About 6.0 hours

\[
0.25N_0 = N_0 - N_0e^{-\lambda t}
\]

\[
e^{-\lambda t} = 0.75 \Rightarrow -\lambda = \frac{\ln 0.75}{3 \text{ hr}}
\]

\[
\lambda = -\frac{\ln 0.75}{3 \text{ hr}}^{-1}
\]

\[
T_{1/2} = \frac{\ln 2}{0.959} = 7.2 \text{ hours}
\]
5. Which of the following statements is false?
   a) When a nucleus undergoes $\beta^+$ decay, the charge of the nucleus decreases.
   b) When a nucleus undergoes $\beta^-$ decay, a neutron in the nucleus turns into a proton.
   c) When a nucleus undergoes $\beta^-$ decay, the Q-value (decay energy) is negative.
   d) When a nucleus undergoes $\beta^+$ decay, the Q-value (decay energy) is positive.
   e) When a nucleus undergoes $\gamma$ decay, the charge of the nucleus remains unchanged.

6. The $^{14}C$ isotope is radioactive with a decay constant $\lambda = 1.21 \times 10^{-4}$ yr$^{-1}$. All living organisms have an activity of 0.255 decays/second per gram of carbon. If a certain dead organism is found to have an activity of 0.060 decays/second per gram of carbon, how long ago did it die?
   a) Between 1000 and 10000 years ago
   b) Less than 10 years ago
   c) More than 10000 years ago
   d) Between 10 and 100 years ago
   e) Between 100 and 1000 years ago

   $\lambda N = 0.060 = \lambda N_0 e^{-\lambda t}$
   $\Rightarrow t = \frac{\ln \frac{0.255}{0.060}}{-1.21 \times 10^{-4}} = 12000$ yr.

7. Consider the nuclear reaction $\frac{1}{2}He + ^{14}N \rightarrow ^{17}O + \frac{1}{2}H$. The atomic masses are $M(He) = 4.002603$ u, $M(N) = 14.003074$ u, $M(O) = 16.999133$ u, $M(H) = 1.007825$ u. What is $Q$, the net kinetic energy released, and what conclusion can be drawn from the sign of $Q$?
   a) $Q = +1.19$ MeV, so some kinetic energy was converted to mass
   b) $Q = +1.19$ MeV, so some mass was converted to kinetic energy
   c) $Q = -1.19$ MeV, so the reaction can't occur
   d) $Q = -1.19$ MeV, so some kinetic energy was converted to mass
   e) $Q = -1.19$ MeV, so some mass was converted to kinetic energy

   $Q = (4.002603 + 14.003074 - 16.999133 - 1.007825)(931.5)$
   $\approx -1.19$ MeV
8. Which of the following statements are true?

- I: The sun releases energy because hydrogen nuclei are undergoing fusion.
- II: Stars whose mass is much smaller than that of our sun will eventually turn into neutron stars or black holes.
- III: When $^{235}U$ undergoes fission into $^{144}Ba$ and $^{89}Kr$, energy is released because $U$ has more binding energy per nucleon than do $Ba$ and $Kr$. \[\text{LESS}\]

a) III is true; I and II are not
b) I and II are true; III is not
c) All three statements are false
d) I and III are true; II is not
e) I is true; II and III are not

9. Only one of the following reactions or decays CANNOT occur. Which is it? For the reactions, assume that the projectile always has enough energy for the reaction to occur, if other applicable conservation laws permit.

\[\rightarrow\]
a) $\nu_\mu + p \rightarrow n + \mu^+$

b) $\pi^- + p \rightarrow n + \pi^0$

c) $\bar{p} + p \rightarrow n + \bar{n}$

d) $p + p \rightarrow p + p + p + \bar{p}$

e) $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Violates $L_\mu$ conservation

10. Which of the following statements is false?

a) In any reaction, the number of baryons (minus anti-baryons) is conserved.

\[\rightarrow\]
b) In any reaction, the number of mesons (minus anti-mesons) is conserved.

c) In any reaction, the number of leptons (minus anti-leptons) is conserved.

d) Anti-baryons are composed of three anti-quarks.

e) Mesons are composed of one quark and one anti-quark.
11. An electrically neutral particle has strangeness $-1$, charm 0, and bottomness $+1$. Which of the following is a possible quark composition for this particle? 

\[ \begin{array}{cccc}
\text{a) } & s & 0 & -1 & 0 & +1 \\
\text{b) } & b & 0 & +1 & 0 & -1 \\
\text{c) } & u & 0 & -1 & 0 & -1 \\
\text{d) } & u & 0 & +1 & 0 & +1 \\
\text{e) } & c & 0 & -1 & -1 & +1 \\
\end{array} \]

12. Consider the hypothetical strong interaction process $B^+ + \Sigma^- \rightarrow \Lambda^+_b + D_s^- + D^0$. Which conservation laws does it satisfy, and which does it violate?

- a) Conserves strangeness, but neither charm nor bottomness
- b) Conserves charm and bottomness, but not strangeness
- c) Conserves strangeness and bottomness, but not charm
- d) Conserves strangeness and charm, but not bottomness
- e) Conserves bottomness, but neither strangeness nor charm

13. A photon strikes a stationary proton, causing the following reaction to occur: $\gamma + p \rightarrow \Lambda + K^+$. What is the minimum energy $E$ that the photon must have if this reaction is to occur?

- a) $E < 650 \text{MeV}$
- b) $650 \leq E < 750 \text{MeV}$
- c) $750 \leq E < 850 \text{MeV}$
- d) $850 \leq E < 950 \text{MeV}$
- e) $E \geq 950 \text{MeV}$

\[ Q = 0 + 938 - 1116 - 494 = -672 \text{ MeV} \]

\[ K_{\text{th}} = \frac{0 + 938 + 116 + 494}{2 \times 938} \approx 913 \text{ MeV} \]

14. According to the General Theory of Relativity, which of the following statements are true?

- I: The effects of acceleration and gravitation cannot be distinguished in a closed laboratory.
- II: To an external observer, a black hole contracts forever towards its Schwarzschild radius, but never quite gets there.
- III: The path of light is unaffected by gravity.

- a) All three statements are true
- b) I and II are true; III is false
- c) I and III are true; II is false
- d) I is true; II and III are false
- e) III is true; I and II are false
15. The Lyman alpha line of hydrogen has a wavelength of 122 nm in the laboratory. For a certain galaxy, the same line is measured to have a wavelength of 300 nm. How far away is the galaxy?

a) About $2.0 \times 10^9$ light years

b) About $4.0 \times 10^9$ light years

c) About $6.0 \times 10^9$ light years

d) About $8.0 \times 10^9$ light years

e) About $1.0 \times 10^{10}$ light years

\[
\frac{\lambda}{\lambda_0} = \frac{300}{122} = \sqrt{\frac{1+\beta}{1-\beta}} = 2.46
\]

\[
\frac{1+\beta}{1-\beta} = 6.05 \quad \Rightarrow \quad \beta = 0.716
\]

\[
R = \frac{V}{H} = \frac{716 \times 3 \times 10^{-8} \text{ m/s}}{0.215 \text{ m/s/deg}} = 1.0 \times 10^{10} \text{ ly}
\]

16. An antiproton of kinetic energy 1200 MeV moves to the right. A proton of kinetic energy 400 MeV moves to the left. The two collide head-on, producing the reaction $\bar{p} + p \rightarrow \pi^0 + X$. What is the maximum mass of $X$ that can be produced in this way?

a) About 3341 MeV/c²

b) About 2762 MeV/c²

c) About 3476 MeV/c²

d) About 1819 MeV/c²

e) About 3204 MeV/c²

\[
E_{CM_f} = M_{\pi^0} c^2 + M_X c^2 \quad \text{for maximum } X \text{ mass}
\]

\[
E_{\bar{p}} = 938 + 1200 = 2138 \text{ MeV}
\]

\[
E_p = 938 + 400 = 1338 \text{ MeV}
\]

\[
\vec{p}_{\bar{p}} = \sqrt{(2138)^2 - (438)^2} \hat{\lambda} = +1921 \hat{\lambda} \text{ MeV/c}
\]

\[
\vec{p}_p = \sqrt{(1338)^2 - (938)^2} \hat{\lambda} = -954 \hat{\lambda} \text{ MeV/c}
\]

\[
\hat{\lambda} \vec{p}_{TOT} = 1921 - 954 = 967 \text{ MeV/c}
\]

\[
E_{CM_i} = \sqrt{E_{\bar{p}}^2 - \vec{p}_{\bar{p}}^2 c^2} = \sqrt{(3476)^2 - (967)^2} = 3339 \text{ MeV}
\]

\[
E_{CM_i} = E_{CM_f} \quad \Rightarrow \quad 3339 = M_{\pi^0} c^2 + M_X c^2 = 135 + M_X c^2
\]

\[
\Rightarrow \quad M_X c^2 = 3204 \text{ MeV}
\]