PHYS 342 (Spring 2023) Test 2, V1 Name: ____________________

Multiple choice (5 pts each) – circle the correct answers.

1. Suppose the 4 electrons in Be all have the same $m_s = 1/2$. Which is the lowest energy allowed configuration under this condition? **Only 1 electron in each** (n, l, m_l)
   (a) $1s^4$
   (b) $1s^2 2s^2$
   (c) $1s2s2p^2$
   (d) $1s2s2p3s$

2. A particle moves in 1D. For $x < 0$, the potential energy is 0. For $x > 0$, the potential energy is 1 eV. If the particle has a total energy of 10 eV, which statement(s) are correct? $\psi(x)$ **is continuous and oscillates for all** x, λ **increases for increasing** U
   (a) the wave function is discontinuous at $x = 0$.
   (b) the de Broglie wavelength for $x < 0$ is greater than that for $x > 0$.
   (c) for $x > 0$, the wave function exponentially decreases towards ∞: $\psi(x) = Ae^{-\kappa x}$.
   (d) for $x < 0$, the wave function exponentially decreases towards $-\infty$: $\psi(x) = Ae^{\kappa x}$.
   (e) none of the above are correct.

3. For this question, don't worry about the spin of the electron. Circle all of the *impossible* states of hydrogen (n, l, m_l). **Required** $n > \ell \geq |m_l|$

   (a) $(5, 0, 0)$ (b) $(2, 1, -1)$ (c) $(5, 5, 2)$
   (d) $(3, 2, 3)$ (e) $(1, 0, 0)$ (f) $(50, 3, 0)$

4. The ${}^3_1H_2$ nucleus has a half life of 12 years. You make one ${}^3_1H_2$ when you are 25 years old. How old will you be when it radioactively decays? **I said I would ask this**
   (a) 37 years old
   (b) 49 years old
   (c) 61 years old
   (d) When it decays can not be predicted.
   (e) none of the above

5. A hydrogen atom in its ground state absorbs a photon and goes to a free electron and proton. The minimum photon energy for this process is 13.6 eV. For the same process in muonic hydrogen (a bound muon and proton in the ground state absorbs a photon and goes to a free muon and proton), what is the minimum photon energy required? **For hydrogen-like, energy is proportional to** M**.**
   (a) more than 13.6 eV.
   (b) less than 13.6 eV.
   (c) 13.6 eV.

Problems: Show *all* work to receive full credit.
Fundamental constants (e, h, masses, etc) are top of the equation page.

10 pts 1. ${}^8_4Be_4$ decays by emission of an alpha particle. a) What is the total energy released? b) What is the speed of the alpha particle?

Counting the number of neutrons and protons, this isotope decays into two alpha particles.

$$E = (8.005305\ u - 2 \times 4.002603\ u)\ c^2\ \times 931.5\ MeV/c^2 = \underline{0.092\ MeV}$$

To conserve momentum, the two alpha particles must be going in opposite directions with the same speed. So each one gets 1/2 of the total energy. The $KE = (0.092\ MeV/2) \times 1.602 \times 10^{-13}\ J/MeV = 7.4 \times 10^{-15}\ J$

$$v = \sqrt{2\ KE/M} = \sqrt{2 \times 7.4 \times 10^{-15}\ J/(4.00 \times 1.66 \times 10^{-27})} = \underline{1.5 \times 10^6\ m/s}$$

This isn't relativistic so it's OK to use the nonrelativistic KE.

10 pts 2. A hydrogen atom in the ground state starts at rest where the magnetic field points in the z-direction with magnitude 2.00 T. The magnetic field gives an interaction energy of $U = -\vec{\mu} \cdot \vec{B}$. It accelerates to a spot 1 cm away where the magnetic field points in the z-direction with a magnitude 2.60 T. a) What is the value of the spin magnetic quantum number? b) What is the kinetic energy of the hydrogen atom?

This is a conservation of energy problem. From the formula sheet, $U = (e/m)S_zB$ **with** $S_z = m_s\hbar$ **with** $m_s = 1/2$ **or** $-1/2$. **Since the hydrogen atom accelerated from rest, the** U **must be decreasing. Therefore, a)** $\underline{m_s = -1/2}$. **For b) use** $KE_i + U_i = KE_f + U_f$ **with** i **meaning initial and** f **meaning final. Since** $KE_i = 0$, $KE_f = U_i - U_f$

$$KE_f = (e/m)\hbar m_s(B_i - B_f)$$

$$= (1.60 \times 10^{-19}/9.11 \times 10^{-31})1.05 \times 10^{-34}(-1/2)(-0.6) = \underline{5.53 \times 10^{-24}\ J}$$

10 pts 3. In an atom, there are two electrons with $m_s = 1/2$. One is in the $2p$ state and the other is in the $3d$ state. a) What is the total number of two electron states with these conditions? b) Suppose the two angular momenta add to give a total orbital angular momentum L. What are the allowed values of L? c) How many states are there for each L?

a) Because both electrons have $m_s = 1/2$, the only multiplicity is coming from the l, $l = 1$ for $2p$ and $l = 2$ for $3d$. The number of m_l with the same l is $2l + 1$. There are 3 states of $2p$ and 5 states of $3d$. The total number of possible states is the product of each possibility: $\underline{15}$. b) $L_{min} = |l_1 - l_2| = 1$ and $L_{max} = l_1 + l_2 = 3$ so L can be <u>1 or 2 or 3</u>. c) There are <u>3</u> states with $L = 1$, <u>5</u> states with $L = 2$, and <u>7</u> states with $L = 3$. (Note the total number of states is again 15)

10 pts 4. A proton is fired directly at a $^{235}_{92}U_{143}$ nucleus. What minimum energy does the proton need to reach the nucleus?

This is again a conservation of energy problem. The distance of closest approach is $d = zZe^2/(4\pi\varepsilon_0 KE)$. This distance is the sum of the radii of the nucleus and the proton, $R = R_0\ A^{1/3}$.

$$d = 1.2\ fm\ 235^{1/3} + 1.2\ fm\ 1^{1/3} = 8.6 \times 10^{-15}\ m$$

$$KE = (1 \times 92 \times (1.60 \times 10^{-19})^2 \times 8.99 \times 10^9 / 8.6 \times 10^{-15})\ J = \underline{2.46 \times 10^{-12}\ J} = \underline{15.4\ MeV}$$

15 pts 5. A particle of mass m experiences a potential which is $U(x) = U_0 > 0$ for $x < 0$ and $U(x) = -U_0$ for $x > 0$. For $-U_0 < E < U_0$, determine the wave function for all x. (Hint: you should probably break it up into a solution for $x < 0$ and a solution for $x > 0$; then use the correct rules to connect the two pieces.)

Break up the solution into the solution for $x < 0$ and the solution for $x > 0$. For $x < 0$, use the solution for $E < U_0$. For $x > 0$, use the solution for $E > -U_0$.

$$x < 0 \qquad \psi(x) = Ae^{k'x} + Be^{-k'x} \qquad \text{with} \qquad k' = \sqrt{2m(U_0 - E)/\hbar^2}$$

$$x > 0 \qquad \psi(x) = Ce^{ikx} + De^{-ikx} \qquad \text{with} \qquad k = \sqrt{2m(E + U_0)/\hbar^2}$$

The region for $x > 0$ could be done with sines and cosines. To figure out relations between the A, B, C, D, you need to get the boundary conditions correct. Because $E < U_0$ for $x < 0$, the wave function has to go to 0 as $x \to -\infty$. This means $B = 0$. The wave function has to be continuous and the derivative of the wave function has to be continuous for this problem.

$$\text{continuous} \qquad A = C + D$$

$$\text{continuous derivative} \qquad k'\,A = ik(C - D) \qquad \text{gives} \qquad C - D = -i\frac{k'}{k}A$$

$$C = \frac{1}{2}\left(1 - i\frac{k'}{k}\right)A$$

$$D = \frac{1}{2}\left(1 + i\frac{k'}{k}\right)A$$

To summarize (not necessary):

$$x < 0 \qquad \psi(x) = Ae^{k'x} \qquad \text{with} \qquad k' = \sqrt{2m(U_0 - E)/\hbar^2}$$

$$x > 0 \qquad \psi(x) = \frac{A}{2k}\left[(k - ik')e^{ikx} + (k + ik')e^{-ikx}\right] \qquad \text{with} \qquad k = \sqrt{2m(E + U_0)/\hbar^2}$$

Can be simplified to (definitely not necessary, but kind of fun)

$$x < 0 \qquad \psi(x) = Ae^{k'x} \qquad \text{with} \qquad k' = \sqrt{2m(U_0 - E)/\hbar^2}$$

$$x > 0 \qquad \psi(x) = A\left[\cos(kx) + \frac{k'}{k}\sin(kx)\right] \qquad \text{with} \qquad k = \sqrt{2m(E + U_0)/\hbar^2}$$

$g = 9.80\ \frac{m}{s^2}$ $h = 6.63 \times 10^{-34}\ J\ s = 4.14 \times 10^{-15}\ eV\ s$ $\hbar = \frac{h}{2\pi}$ $c = 3.00 \times 10^{8}\ \frac{m}{s}$

$M_{elec} = 9.11 \times 10^{-31}\ kg$ $M_{prot} = 1.67 \times 10^{-27}\ kg$ $M_{muon} = 1.88 \times 10^{-28}\ kg$

$1.60 \times 10^{-19}\ J = 1\ eV$ $e = 1.60 \times 10^{-19}$ C $1/(4\pi\varepsilon_0) = 8.99 \times 10^{9}$ N m^2/C^2

Galilean relativity	$x' = x - ut, v'_x = v_x - u$	2.1
Einstein's postulates	(1) The laws of physics are the same in all inertial frames. (2) The speed of light has the same value c in all inertial frames.	2.3
Time dilation	$\Delta t = \dfrac{\Delta t_0}{\sqrt{1 - u^2/c^2}}$ (Δt_0 = proper time)	2.4
Length contraction	$L = L_0\sqrt{1 - u^2/c^2}$ (L_0 = proper length)	2.4
Velocity addition	$v = \dfrac{v' + u}{1 + v'u/c^2}$	2.4
Doppler effect (source and observer separating)	$f' = f\sqrt{\dfrac{1 - u/c}{1 + u/c}}$	2.4
Lorentz transformation	$x' = \dfrac{x - ut}{\sqrt{1 - u^2/c^2}}$, $y' = y,\ z' = z,$ $t' = \dfrac{t - (u/c^2)x}{\sqrt{1 - u^2/c^2}}$	2.5
Lorentz velocity transformation	$v'_x = \dfrac{v_x - u}{1 - v_x u/c^2}$, $v'_y = \dfrac{v_y\sqrt{1 - u^2/c^2}}{1 - v_x u/c^2}$, $v'_z = \dfrac{v_z\sqrt{1 - u^2/c^2}}{1 - v_x u/c^2}$	2.5
Clock synchronization	$\Delta t' = \dfrac{uL/c^2}{\sqrt{1 - u^2/c^2}}$	2.5
Relativistic momentum	$\vec{\mathbf{p}} = \dfrac{m\vec{\mathbf{v}}}{\sqrt{1 - v^2/c^2}}$	2.7
Relativistic kinetic energy	$K = \dfrac{mc^2}{\sqrt{1 - v^2/c^2}} - mc^2$	2.7
Rest energy	$E_0 = mc^2$	2.7
Relativistic total energy	$E = K + E_0 = \dfrac{mc^2}{\sqrt{1 - v^2/c^2}}$	2.7
Momentum-energy relationship	$E = \sqrt{(pc)^2 + (mc^2)^2}$	2.7
Extreme relativistic approximation	$E \cong pc$	2.7
Conservation laws	In an isolated system of particles, the total momentum and the relativistic total energy remain constant.	2.8

Hubble's law	$v = H_0 d$	15.1
Number density of photons	$N/V = (2.03 \times 10^7 \text{photons/m}^3 \cdot \text{K}^3)T^3$	15.2
Energy density of photons	$U = (4.72 \times 10^3\ \text{eV/m}^3 \cdot \text{K}^4)T^4$	15.2
Gravitational frequency change	$\Delta f/f = gH/c^2$	15.4
Deflection of starlight	$\theta = 2GM/Rc^2$	15.5
Perihelion precession	$\Delta\phi = \dfrac{6\pi GM}{c^2 r_{\text{min}}(1 + e)}$	15.5
Schwarzschild radius	$r_S = 2GM/c^2$	15.6
Age of matter-dominated universe	$t = 1/\sqrt{6\pi G\rho_m}$	15.7
Age of radiation-dominated universe	$t = \sqrt{3/32\pi G\rho_r}$	15.7
Temperature of universe at age t	$T = \dfrac{1.5 \times 10^{10}\ \text{s}^{1/2} \cdot \text{K}}{t^{1/2}}$	15.8
Fraction of photons above E_0	$f = 0.42e^{-E_0/kT} \times \left[\left(\frac{E_0}{kT}\right)^2 + 2\left(\frac{E_0}{kT}\right) + 2\right]$	15.9
Critical density of universe	$\rho_{cr} = \dfrac{3H^2}{8\pi G} = 0.97 \times 10^{-26}\ \text{kg/m}^3$	15.10

Double-slit maxima	$y_n = n\frac{\lambda D}{d} \quad n = 0, 1, 2, 3, \ldots$	3.1
Bragg's law for X-ray diffraction	$2d\sin\theta = n\lambda \quad n = 1, 2, 3, \cdots$	3.1
Energy of photon	$E = hf = hc/\lambda$	3.2
Maximum kinetic energy of photoelectrons	$K_{max} = eV_s = hf - \phi$	3.2
Cutoff wavelength	$\lambda_c = hc/\phi$	3.2
Stefan's law	$I = \sigma T^4$	3.3
Wien's displacement law	$\lambda_{max} T = 2.8978 \times 10^{-3}\ \mathrm{m \cdot K}$	3.3

Rayleigh-Jeans formula	$I(\lambda) = \frac{2\pi c}{\lambda^4} kT$	3.3
Planck's blackbody distribution	$I(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1}$	3.3
Compton scattering	$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_e c^2}(1 - \cos\theta),$ $\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$	3.4
Bremsstrahlung	$\lambda_{min} = hc/K = hc/e\Delta V$	3.5
Pair production	$hf = E_+ + E_- = (m_e c^2 + K_+) + (m_e c^2 + K_-)$	3.5
Electron-positron annihilation	$(m_e c^2 + K_+) + (m_e c^2 + K_-) = E_1 + E_2$	3.5

De Broglie wavelength	$\lambda = h/p$	4.1
Single slit diffraction	$a\sin\theta = n\lambda \quad n = 1, 2, 3, \ldots$	4.2
Classical position-wavelength uncertainty	$\Delta x \Delta\lambda \sim \varepsilon\lambda^2$	4.3
Classical frequency-time uncertainty	$\Delta f\, \Delta t \sim \varepsilon$	4.3
Heisenberg position-momentum uncertainty	$\Delta x \Delta p_x \sim \hbar$	4.4
Heisenberg energy-time uncertainty	$\Delta E \Delta t \sim \hbar$	4.4

Statistical momentum uncertainty	$\Delta p_x = \sqrt{(p_x^2)_{av} - (p_{x,av})^2}$	4.4
Wave packet (discrete k)	$y(x) = \sum A_i \cos k_i x$	4.5
Wave packet (continuous k)	$y(x) = \int A(k) \cos kx\, dk$	4.5
Group speed of wave packet	$v_{group} = \frac{d\omega}{dk}$	4.6

Time-independent Schrödinger equation	$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + U(x)\psi(x) = E\psi(x)$	5.3
Time-dependent Schrödinger equation	$\Psi(x, t) = \psi(x)e^{-i\omega t}$	5.3
Probability density	$P(x) = \lvert\psi(x)\rvert^2$	5.3
Normalization condition	$\int_{-\infty}^{+\infty} \lvert\psi(x)\rvert^2\, dx = 1$	5.3
Probability in interval x_1 to x_2	$P(x_1 : x_2) = \int_{x_1}^{x_2} \lvert\psi(x)\rvert^2\, dx$	5.3
Average or expectation value of $f(x)$	$[f(x)]_{av} = \int_{-\infty}^{+\infty} \lvert\psi(x)\rvert^2 f(x)\, dx$	5.3
Constant potential energy, $E > U_0$	$\psi(x) = A\sin kx + B\cos kx,$ $k = \sqrt{2m(E - U_0)/\hbar^2}$	5.4
Constant potential energy, $E < U_0$	$\psi(x) = Ae^{k'x} + Be^{-k'x},$ $k' = \sqrt{2m(U_0 - E)/\hbar^2}$	5.4

Infinite potential energy well	$\psi_n(x) = \sqrt{\frac{2}{L}}\sin\frac{n\pi x}{L},$ $E_n = \frac{h^2 n^2}{8mL^2}\ (n = 1, 2, 3, \ldots)$	5.4
Two-dimensional infinite well	$\psi(x, y) = \frac{2}{L}\sin\frac{n_x \pi x}{L}\sin\frac{n_y \pi y}{L}$ $E = \frac{h^2}{8mL^2}(n_x^2 + n_y^2)$	5.4
Simple harmonic oscillator ground state	$\psi(x) = (m\omega_0/\hbar\pi)^{1/4}\, e^{-(\sqrt{km}/2\hbar)x^2}$	5.5
Simple harmonic oscillator energies	$E_n = (n + \frac{1}{2})\hbar\omega_0\ (n = 0, 1, 2, \ldots)$	5.5
Potential energy step, $E > U_0$	$\psi_0(x < 0) = A\sin k_0 x + B\cos k_0 x$ $\psi_1(x > 0) = C\sin k_1 x + D\cos k_1 x$	5.6
Potential energy step, $E < U_0$	$\psi_0(x < 0) = A\sin k_0 x + B\cos k_0 x$ $\psi_1(x > 0) = Ce^{k_1 x} + De^{-k_1 x}$	5.6

Scattering impact parameter	$b = \frac{zZ}{2K}\frac{e^2}{4\pi\varepsilon_0}\cot\frac{1}{2}\theta$	6.3
Fraction scattered at angles $> \theta$	$f_{>\theta} = nt\pi b^2$	6.3
Rutherford scattering formula	$N(\theta) = \frac{nt}{4r^2}\left(\frac{zZ}{2K}\right)^2\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\frac{1}{\sin^4\frac{1}{2}\theta}$	6.3
Distance of closest approach	$d = \frac{1}{4\pi\varepsilon_0}\frac{zZe^2}{K}$	6.3
Balmer formula	$\lambda = (364.5\,\text{nm})\frac{n^2}{n^2-4}$ $(n = 3, 4, 5, \ldots)$	6.4
Radii of Bohr orbits in hydrogen	$r_n = \frac{4\pi\varepsilon_0\hbar^2}{me^2}n^2 = a_0n^2$ $(n = 1, 2, 3, \ldots)$	6.5
Energies of Bohr orbits in hydrogen	$E_n = -\frac{me^4}{32\pi^2\varepsilon_0^2\hbar^2}\frac{1}{n^2}$ $= \frac{-13.60\,\text{eV}}{n^2} \quad (n = 1, 2, 3, \ldots)$	6.5
Excitation energy of level n	$E_n - E_1$	6.5
Binding (or ionization) energy of level n	$\lvert E_n \rvert$	6.5
Hydrogen wavelengths in Bohr model	$\lambda = \frac{64\pi^3\varepsilon_0^2\hbar^3c}{me^4}\left(\frac{n_1^2n_2^2}{n_1^2-n_2^2}\right)$ $= \frac{1}{R_\infty}\left(\frac{n_1^2n_2^2}{n_1^2-n_2^2}\right)$	6.5
Single-electron atoms with $Z > 1$	$r_n = \frac{a_0n^2}{Z}$, $E_n = -(13.60\,\text{eV})\frac{Z^2}{n^2}$	6.5
Reduced mass of proton-electron system	$m = \frac{m_em_p}{m_e+m_p}$	6.8

Orbital angular momentum	$\lvert\vec{\mathbf{L}}\rvert = \sqrt{l(l+1)}\hbar$ $(l = 0, 1, 2, \ldots)$	7.2
Orbital magnetic quantum number	$L_z = m_l\hbar$ $(m_l = 0, \pm1, \pm2, \ldots, \pm l)$	7.2
Spatial quantization	$\cos\theta = \frac{L_z}{\lvert\mathbf{L}\rvert} = \frac{m_l}{\sqrt{l(l+1)}}$	7.2
Angular momentum uncertainty relationship	$\Delta L_z\Delta\phi \geqslant \hbar$	7.2
Hydrogen quantum numbers	$n = 1, 2, 3, \ldots$ $l = 0, 1, 2, \ldots, n-1$ $m_l = 0, \pm1, \pm2, \ldots, \pm l$	7.3
Hydrogen energy levels	$E_n = -\frac{me^4}{32\pi^2\varepsilon_0^2\hbar^2}\frac{1}{n^2}$	7.3
Hydrogen wave functions	$\psi_{n,l,m_l}(r,\theta,\phi) =$ $R_{n,l}(r)\Theta_{l,m_l}(\theta)\Phi_{m_l}(\phi)$	7.3
Radial probability density	$P(r) = r^2\lvert R_{n,l}(r)\rvert^2$	7.4
Angular probability density	$P(\theta,\phi) = \lvert\Theta_{l,m_l}(\theta)\Phi_{m_l}(\phi)\rvert^2$	7.5
Orbital magnetic dipole moment	$\vec{\boldsymbol{\mu}}_L = -(e/2m)\vec{\mathbf{L}}$	7.6
Spin magnetic dipole moment	$\vec{\boldsymbol{\mu}}_S = -(e/m)\vec{\mathbf{S}}$	7.6
Spin angular momentum	$\lvert\vec{\mathbf{S}}\rvert = \sqrt{s(s+1)}\hbar = \sqrt{3/4}\hbar$ (for $s = 1/2$)	7.6
Spin magnetic quantum number	$S_z = m_s\hbar \; (m_s = \pm 1/2)$	7.6
Spectroscopic notation	$s\ (l = 0), p(l = 1), d(l = 2),$ $f(l = 3), \ldots$	7.7
Selection rules for photon emission	$\Delta l = \pm1 \quad \Delta m_l = 0, \pm1$	7.7, 7.8
Normal Zeeman effect	$\Delta\lambda = \frac{\lambda^2}{hc}\Delta E = \frac{\lambda^2}{hc}\mu_B B$	7.8
Fine-structure estimate	$\Delta E = mc^2\alpha^4/n^5 \quad (\alpha\approx 1/137)$	7.9

Pauli exclusion principle	*No two electrons in a single atom can have the same set of quantum numbers* (n, l, m_l, m_s).	8.1
Filling order of atomic subshells	$1s, 2s, 2p, 3s, 3d, 4s, 3d,$ $4p, 5s, 4d, 5p, 6s, 4f, 5d,$ $6p, 7s, 5f, 6d$	8.2
Capacity of subshell nl	$2(2l+1)$	8.2
Energy of screened electron	$E_n = (-13.6\,\text{eV})\frac{Z_{\text{eff}}^2}{n^2}$	8.3
Moseley's law for K_α X rays	$\Delta E = (10.2\,\text{eV})(Z-1)^2$	8.5
Adding angular momenta l_1, m_{l1} and l_2, m_{l2}	$L_{\text{max}} = l_1 + l_2,$ $L_{\text{min}} = \lvert l_1 - l_2\rvert,$ $M_L = m_{l1} + m_{l2}$	8.6
Hund's rules for ground state	First $S = M_{S,\text{max}}$, then $L = M_{L,\text{max}}$	8.6

Nuclear radius	$R = R_0 A^{1/3}, R_0 = 1.2\text{ fm}$	12.2
Nuclear binding energy	$B = [Nm_n + Zm(^1_1\text{H}_0) - m(^A_Z\text{X}_N)]c^2$	12.3
Proton separation energy	$S_p = [m(^{A-1}_{Z-1}\text{X}'_N) + m(^1\text{H}) - m(^A_Z\text{X}_N)]c^2$	12.3
Neutron separation energy	$S_n = [m(^{A-1}{}_Z\text{X}_{N-1}) + m_n - m(^A_Z\text{X}_N)]c^2$	12.3
Range of exchanged particle	$mc^2 = \hbar c/x$	12.4
Activity	$a = \lambda N, \lambda = \ln 2/t_{1/2} = 0.693/t_{1/2}$	12.5
Radioactive decay law	$N = N_0 e^{-\lambda t}, a = a_0 e^{-\lambda t}$	12.5
Q value of decay $\text{X} \to \text{X}' + \text{x}$	$Q = [m_\text{X} - (m_{\text{X}'} + m_\text{x})]c^2$	12.6
Q value of alpha decay	$Q = [m(\text{X}) - m(\text{X}') - m(^4\text{He})]c^2$	12.7
Kinetic energy of alpha particle	$K_\alpha \cong Q(A-4)/A$	12.7
Q values of beta decay	$Q_{\beta^-} = [m(^A\text{X}) - m(^A\text{X}')]c^2$, $Q_{\beta^+} = [m(^A\text{X}) - m(^A\text{X}') - 2m_e]c^2$	12.8
Recoil in gamma decay	$K_R = E_\gamma^2/2Mc^2$	12.9

Forces	Strong, electromagnetic, weak, gravitational	14.1
Field particles	Gluon (g), photon (γ), weak boson ($W^\pm, Z^0$), graviton	14.1
Leptons	$e^-, \nu_e, \mu^-, \nu_\mu, \tau^-, \nu_\tau$	14.2
Mesons	$\pi^\pm, \pi^0, K^\pm, K^0, \overline{K}^0, \eta, \rho^\pm, \eta', D^\pm, \psi, B^\pm, \Upsilon, \ldots$	14.2
Baryons	$p, n, \Lambda^0, \Sigma^{\pm,0}, \Xi^{-,0}, \Omega^-, \ldots$	14.2
Conservation of lepton number L	*In any process, L_e, L_μ, and L_τ remain constant.*	14.3
Conservation of baryon number B	*In any process, B remains constant.*	14.3
Conservation of strangeness S	*In strong and electromagnetic processes, S remains constant; in weak processes,* $\Delta S = 0$ or ± 1.	14.3
Q value in decays or reactions	$Q = (m_i - m_f)c^2$	14.5, 14.6
Threshold energy in reactions	$K_{th} = -Q(m_1 + m_2 + m_3 + m_4 + m_5 + \cdots)/2m_2$	14.6
Quarks	u, d, c, s, t, b	14.7

SOME PARTICLE MASSES

	kg	u	MeV/c^2
Electron	$9.1093829 \times 10^{-31}$	$5.485799095 \times 10^{-4}$	0.51099893
Proton	$1.67262178 \times 10^{-27}$	1.0072764668	938.27205
Neutron	$1.67492735 \times 10^{-27}$	1.0086649160	939.56538
Deuteron	$3.3435835 \times 10^{-27}$	2.0135532127	1875.61286
Alpha	$6.6446568 \times 10^{-27}$	4.001506179	3727.3792

CONVERSION FACTORS

$1\text{ eV} = 1.60217657 \times 10^{-19}\text{ J}$

$1\text{ u} = 931.49406\text{ MeV}/c^2$

$= 1.66053892 \times 10^{-27}\text{ kg}$

$1\text{ y} = 3.156 \times 10^7\text{ s} \cong \pi \times 10^7\text{ s}$

$1\text{ barn (b)} = 10^{-28}\text{ m}^2$

$1\text{ curie (Ci)} = 3.7 \times 10^{10}\text{ decays/s}$

$1\text{ light-year} = 9.46 \times 10^{15}\text{ m}$

$1\text{ parsec} = 3.26\text{ light-year}$

	Z	A	Atomic mass (u)	*Abundance* or Half-life
H	1	1	1.0078250	*99.985%*
		2	2.014102	*0.015%*
		3	3.016049	12.3 y
He	2	3	3.016029	*0.000137%*
		4	4.002603	*99.999863%*
Li	3	6	6.015123	*7.59%*
		7	7.016005	*92.41%*
		8	8.022487	0.84 s
Be	4	7	7.016930	53.2 d
		8	8.005305	0.07 fs
		9	9.012182	*100%*
		10	10.013534	1.5 My
		11	11.021658	13.8 s
B	5	8	8.024607	0.77 s
		9	9.013329	0.85 as
		10	10.012937	*19.8%*
		11	11.009305	*80.2%*
		12	12.014352	20.2 ms