Chapter 32 Nuclear Physics

Section 32-1 Nuclear Structure The structure of the nucleus had been determined by 1932 to consist of protons and neutrons (both generally called nucleons). The atomic mass number A is equal to the sum of the number of protons Z (Z = the atomic number) and the number of neutrons N (that is, A = Z + N). An isotope of an element has the same number of protons as the element, but a different number of neutrons (a neutral atom has an identical number of protons and electrons, and the electrons determine the chemical properties). Symbolically, isotopes (nuclides) are represented by ${}^{A}_{Z}X$, where X is the chemical symbol of the element. Elements naturally possess isotopes and the reported atomic mass is just the weighted average of the isotope's relative abundances. Masses of atomic scale are today measured in unified atomic mass units (u) defined by specifying that a neutral carbon-12 atom has a mass of exactly 12.000 000 u.

- **Nuclear Size and Density** Scattering experiments led to the following formula for the radius of the nucleus: $R = 1.2 \times 10^{-15}\ \text{m}\ A^{1/3} = 1.2\ \text{fm}\ A^{1/3}$. A simple calculation of the density of the nucleus (where mass is proportional to A and volume is proportional to A) yields a typical value of $2.3 \times 10^{17}\ \text{kg/m}^3$.

- **Nuclear Stability** If you plot (Figure 32-1) the stable nuclei as N versus Z, you find that as the atomic number gets larger, N must get larger more quickly than Z (i.e. a nucleus needs more neutrons than protons to hold it together).

Section 32-2 Radioactivity Nuclei can decay through 5 different processes:

1) Alpha decay: here the nucleus (usually a massive one) emits a helium nucleus (called an alpha particle). Symbolically the decay reaction is ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q$, where X is the "parent" nucleus, Y is the "daughter" nucleus, and Q is the disintegration energy.

2) Negative β decay (β^-): here inside an individual neutron, the weak nuclear force acts to convert a neutron into a proton. The reaction is ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu} + Q$.

3) Positive β decay (β^+): here inside an individual proton, the weak nuclear force acts to convert a proton into a neutron. The reaction is ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu + Q$.

4) Electron Capture: in this process, a proton in the nucleus "absorbs" an inner electron (90% of the time from the n=1 shell). The reaction is ${}^{0}_{-1}e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \nu + Q$.

5) Gamma Decay: After undergoing a decay or being excited, a nucleus is left in an excited state and decays to its ground state by emitting a photon– in this case a gamma ray. The reaction is ${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$.

In each of the beta decays and electron capture, an additional particle is produced (either a ν or $\bar{\nu}$). The ν is a neutrino– a massless, chargeless particle which interacts very weakly with matter, but whose production is required by conservation of energy and momentum in these three decays.

Section 32-3 Radioactive Decay Law Naturally radioactive nuclei statistically follow a decay process that can be described mathematically by: $\Delta N/\Delta t = -\lambda N$. The negative of the rate of decay ($-\Delta N/\Delta t$) is called the activity and can be written $R = R_0 e^{-\lambda t}$. The number of nuclei which remain is then given by $N = N_0 e^{-\lambda t}$. Both of these expressions are exponential decays (see Figs 32-5,6) where N or R decrease by half for each half-life of time that passes.

- One can find the decay constant λ from either of the above expressions as: $\lambda = 0.693/T_{1/2}$. On a plot of *ln* R (or *ln* N) versus time, the slope is equal to ($-\lambda$). Furthermore, the connection between R_0 and N_0 is: $R_0 = \lambda N_0$.

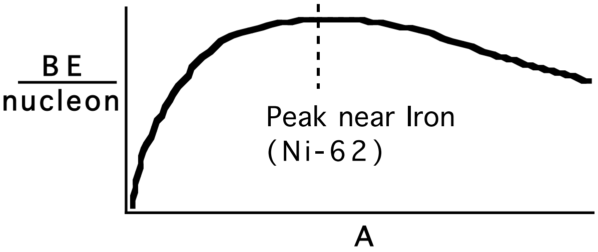
- **Radioactive Dating** A nuclei which decays with a known half-life is like a ticking clock. Its relative presence in a material can used to determine how old the object is. This is the case with isotope of carbon called carbon-14 (^{14}C). Carbon-14 has a half-life of 5730 years and is regularly replenished in the atmosphere and taken up by plants, where it starts decaying when the plant is cut down or dies. The relative activity of wood can then be used to date an archaeological sample.

Section 32-4 Nuclear Binding Energy When the mass of a nucleus is compared to the total mass of it's protons and neutrons, the nucleus mass is found to be less than the sum of the total mass of it's protons and neutrons. This difference in mass (Δm) is called the mass defect. From special relativity, we know that this "missing mass" must have gone into the binding energy that holds the nucleons together:

$$BE = \Delta m\, c^2 = [Z\, M(^1_1H) + (A - Z)\, M_n - M(^A_ZX)\,]\, c^2$$

Note that the mass of a neutral hydrogen atom is used, *not* the mass of a proton.

If we plot the binding energy per nucleon versus the atomic mass number, we get Figure 30.9. Notice that the curve peaks near Iron (Fe), which will determine which elements can undergo fission and fusion.



- **Energy in Nuclear Reactions** In reactions between colliding nuclei, the products may different than the reactants and may be radioactive as well. The Q value of a reaction is the mass-energy difference between the reactants and the products. An exoergic reaction releases energy (Q>0) and an endoergic reaction requires energy to proceed (Q<0). The Q value is given by $Q = (\Sigma\, m_{input} - \Sigma\, m_{out})\, c^2 = E_{in} - E_{out}$. The general reaction would be: $x + X \rightarrow y + Y + Q$

Section 32-8 Nuclear Force The force which holds the positively charged repulsive protons together (as well as neutral neutrons) is called the strong nuclear force. The following table (a version of Table 32-5) gives a comparison of the different forces we will have seen in these two semesters of physics:

Type of Force	**Relative Strength**	**Range**
Strong Nuclear	1	$\sim 10^{-15}$ m
Electromagnetic	$\frac{1}{137}$	$\frac{1}{r^2}$ (i.e. infinite)
Weak nuclear	$\sim 10^{-5}$	10^{-17} m
Gravitational	$\sim 6 \times 10^{-39}$	$\frac{1}{r^2}$ (i.e. infinite)