THE NUCLEUS AND RADIOACTIVITY

The nuclear atom

The nucleus contains two types of “particles”:

PROTONS.

$m_p = 1.67265 \times 10^{-27}$ kg, $q = + 1.6 \times 10^{-19}$ Coulombs

NEUTRONS

$m_n = 1.67500 \times 10^{-27}$ kg, $q = 0$

Nomenclature

Z = number of protons, A = number of nucleons or particles in the nucleus. So

Number of Neutrons = A – Z

Using symbols for the elements from the periodic table,

$^{A}_{Z}$Element: $^{4}_{2}\mathrm{He}$ is “helium-four”

$^{3}_{2}\mathrm{He}$ is “helium-three”

which have the same Z but different A, called ISOTOPES. $^{4}\mathrm{He}$ has two neutrons and two protons, and $^{3}\mathrm{He}$ has one neutron and two protons. The number of electrons in the “orbits” around the nucleus is equal to Z, or 2 in the case of He.

Atomic Mass Units: $u = 1.6605 \times 10^{-27}$ kg $= 931.5$ MeV/c^2

Forces inside the nucleus

Protons repel each other via Coulomb force. But neutrons and protons attract each other via a short range very strong force which works only inside the nucleus (or in collisions in particle accelerators)

Reminder of Coulomb force $F = k\, q_1\, q_2 / r^2$

$k = 9 \times 10^9$ Newton m^2/C^2

Stability of nuclei

Thanks to strong force, a set of STABLE nuclei (and atoms) exists, otherwise the Coulomb repulsion would make protons fly apart from each other.

Density of nuclear matter is rather uniform, Rutherford measured the size of nuclei for various substances (he is the person who measured the scattering of alpha-particles from Au). Today we can use that the radius of a nucleus is approximately

$R_N = (1.2 \times 10^{-15})\, A^{1/3}$ meters.

If we test this with Hydrogen (H), A = 1, we get

$R_N = 1.2 \times 10^{-15}$ meters, $R_{Bohr} = 5 \times 10^{-11}$ meters

Ratio: $R_{Bohr}/R_N \approx 4 \times 10^4$

NOTE: if we scale for $R_N = 0.1$ m, then R_{Bohr} about 4 km (3miles)! Electron will be "downtown" from this room.

STABLE AND UNSTABLE NUCLEI

For low Z materials the number of protons and neutrons is roughly equal, but as Z increases the number of neutrons increases above the number of protons to compensate for the "long range" of the Coulomb force. See next transparency/page.

Too many neutrons or too many protons in a nucleus will make them unstable.

Neutrons are unstable particles.

Neutron → Proton + electron $T_{1/2} = 10.4$ minutes

Radioactive Decay

Radioactivity is the emission of particles (matter particles or photons) and energy from a nucleus.

ALPHA PARTICLES

They are nuclei of ^{4}He ($Z = 2$), they carry a charge of $+2e$, $A=4$

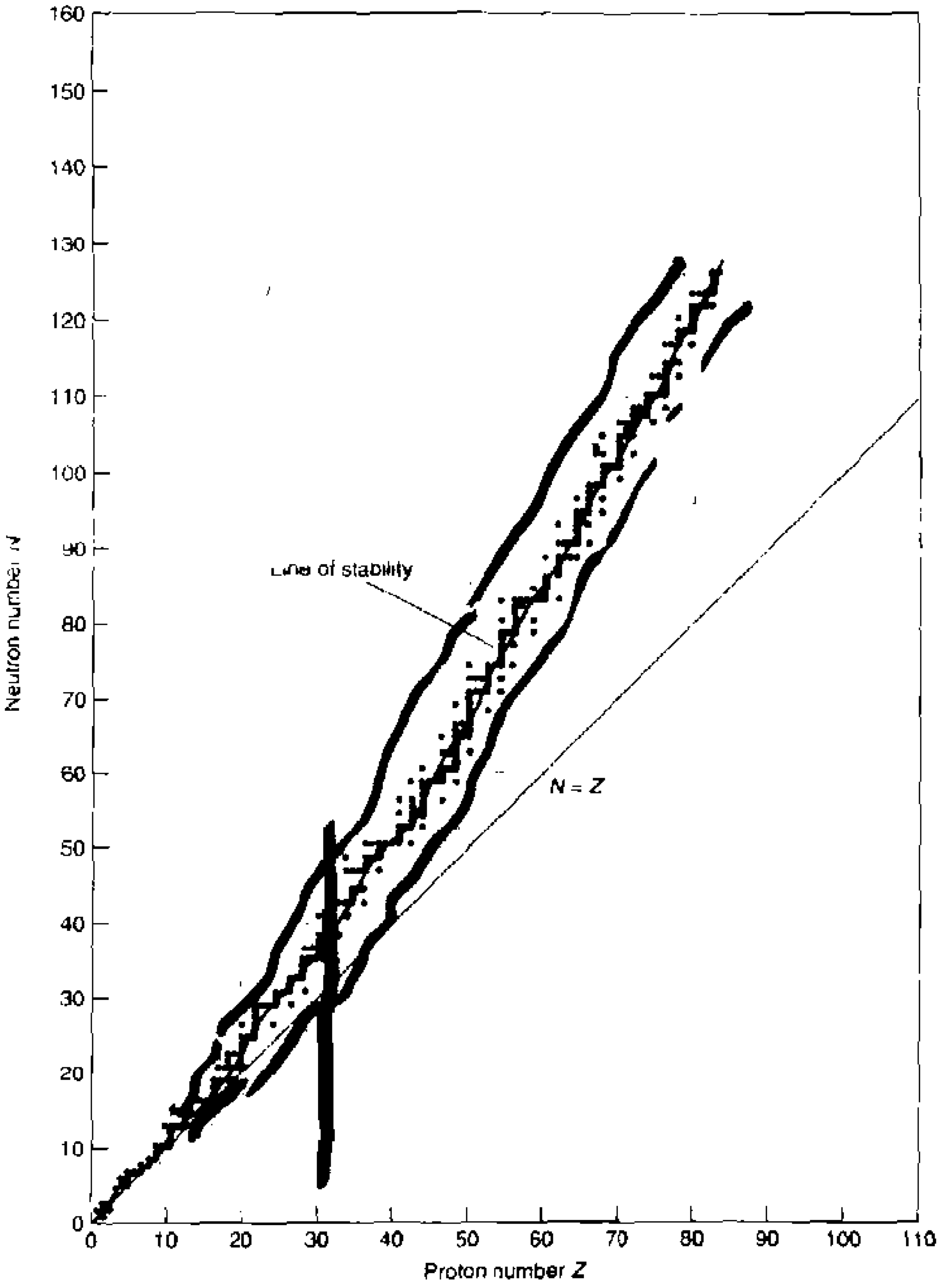
BETA PARTICLES

Electrons, or β^- They carry a charge $-e$, mass m_e

Positrons, or β^+ They carry a charge $+e$, mass m_e

GAMMA PARTICLES/RADIATION

Photons Usually KeV or MeV energies



[illegible] Plot of neutron number N versus proton number Z for the known nuclides. The 266 stable nuclides are indicated by the black dots. The shaded area represents the known unstable, or radioactive, nuclides whose lifetimes are longer than about a millisecond. The curved line through the stable nuclides is called the *line of stability.*

EXAMPLES

α – RADIATION.

$^{A}_{Z}X \rightarrow {}^{4}_{2}He^{++} + {}^{A-4}_{Z-2}Y$ (plus two electrons from outside nucleus)

X is the "parent", Y is the "daughter" nucleus....

β^{-} - RADIATION.

$^{A}_{Z}X \rightarrow e^{-} + {}^{A}_{Z+1}Y$

A neutron has decayed and converted to a proton, which increases Z by ONE.

γ – RADIATION

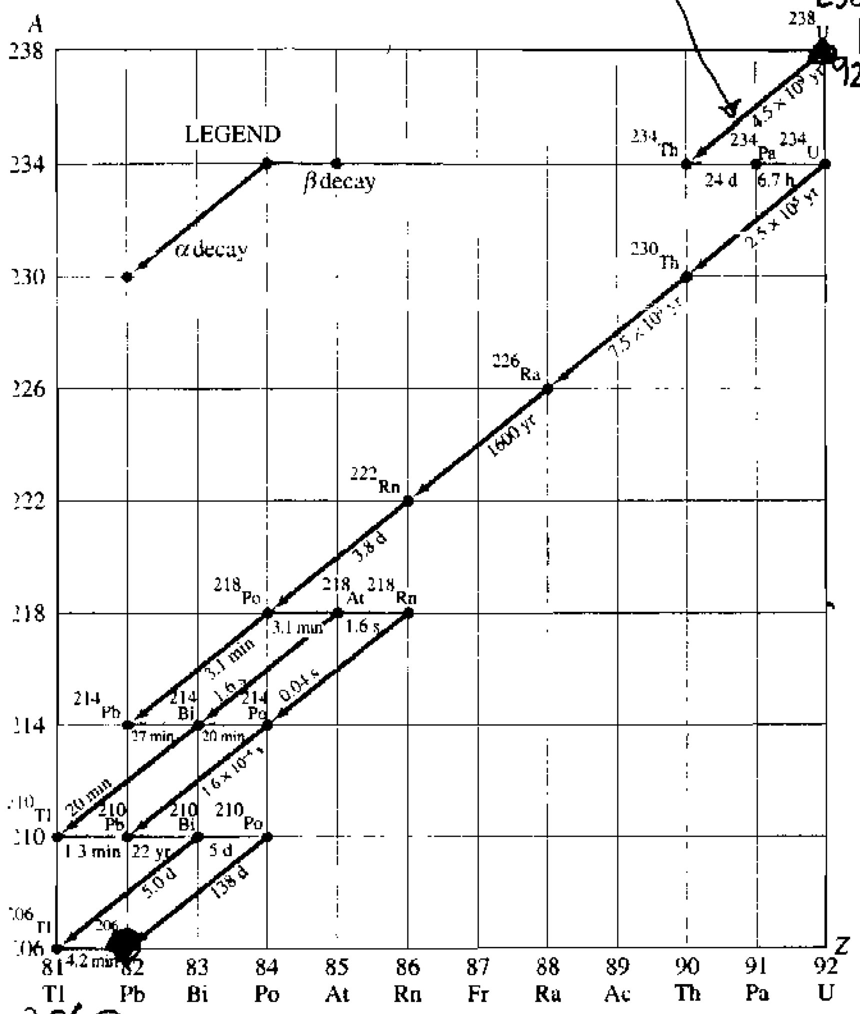
$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + hf$

The * means that the nucleus (which has internal energy levels) was in an excited state, much like electrons in the atomic levels can be in excited states and decay to the ground state (or other states) by emitting photons.

SEE NEXT TRANSPARENCY (PAGE) WITH DECAY OF ^{238}U

Remember that alpha decays reduce A by 4 and Z by 2, and that beta (electron) decays keep A constant and Z increases by one. In between there may be several gamma-rays emitted since the daughter nuclei may be in an excited state.

$T_{1/2} = 4.5 \times 10^9$ years



$^{238}_{92}U$

$^{206}_{82}Pb$

FIGURE 30–10 Decay series beginning with $^{238}_{92}$U. Nuclei in the series are specified by a dot representing *A* and *Z* values. Half-lives are given in seconds (s), minutes (min), hours (h), days (d), or years (yr). Note that a horizontal arrow represents β decay (*A* does not change), whereas a diagonal line represents α decay (*A* changes by 4, *Z* changes by 2).

RADIOACTIVITY, A STOCHASTIC PROCESS

The decay of nuclei is a "probabilistic" occurrence. Some unstable isotopes or atoms take a very long time to return to their final stable state, and some return very fast.

If we start at a time $t = 0$ with N_0 atoms, at a later time "t" we will have left

$$N = N_0 e^{-\lambda t}$$

atoms. The constant λ is called "THE RATE CONSTANT" and is unique for each isotope. Units of lambda are 1/second.

A better known quantity (at least in general) is the HALF LIFE, which is the TIME that will take HALF the sample to have decayed, we call it $T_{1/2}$. One can relate the RATE CONSTANT and the HALF LIFE:

$$(1/2)\, N_0 = N_0\, e^{-\lambda T(1/2)}$$

If one takes the natural logarithm of both sides one gets

$$-\ln 2 = -\lambda T_{1/2} = -0.693$$

$$\text{So } \lambda = 0.693/\, T_{1/2}$$

ACTIVITY

The activity of a radioactive sample refers to the number of decays that occur per second.

The activity is given by:

$$\Delta N/\Delta t = (0.693/T_{1/2})\, N_0\, e^{-(0.693/T\_(1/2))} = (0.693/T_{1/2})\, N$$

so the activity is proportional to the number of nuclei present, and at one half life not only the number of nuclei available for decay decreases to half its value at time t = 0, but also the number of decays per second decreases to half. If you ever work with a radioactive source you will see that it lists its activity at a given time. Its activity will decrease depending on its half-life.

It used to be measured in Curie (Ci), with 1 Ci = 3.7×10^{10} decays/s

The actual SI unit of activity is the Becquerel (after the discoverer of radioactivity), with 1 Bq = 1 decay/second.

The following information is not needed for this class. For radiation therapy the current units are the **rem** or the **sievert.** The rem stands for rad equivalent men, which is a unit which measures the amount of damage done to humans. One **rad** of any type of radiation is the amount of that specific radiation which deposits 0.01 Joules/kg of any material. The "equivalent in men" takes into account that different tissues absorb radiation in different ways depending on what type of radiation it receives and what the tissue is (bone absorbs more radiation than cells). Section 32-7 of Walker's book deals with effects of radiation and radiation therapy. A much better account is given in Giancoli's "Physics", 5th edition, Sections 31-4, 5, 6 and 7, if you need Radiation Medicine for the MCAT, other exams, yourself, or curiosity.

→ Normal dose we receive per year ≈ 0.36 rem/person/year

→ Dentist ⇒ 0.04 rem/year.

→ Dose > 500 rem in a short time is fatal.