

Nuclear Stability and Radioactivity

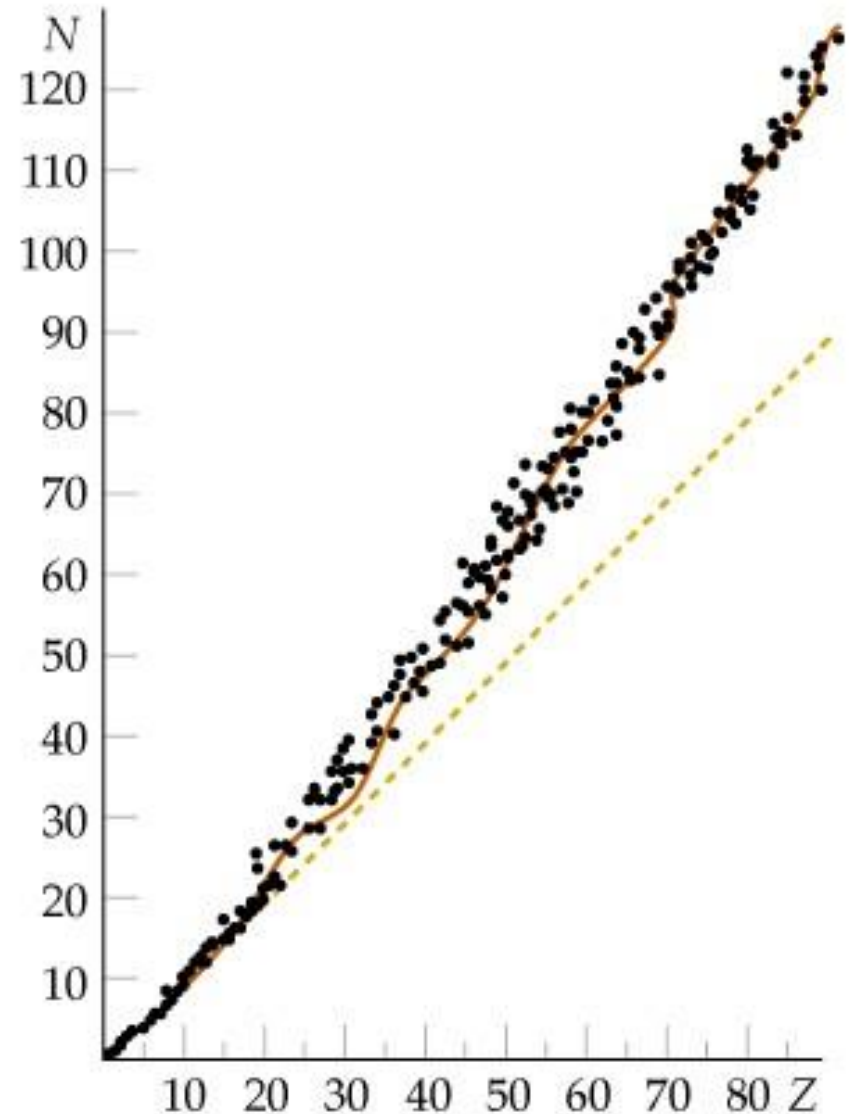
Year 11 Physics Term 2 Week9

Nuclear Stability

- Of the 2500 known nuclides, less than 300 are stable.
- The others are unstable and decay to form other nuclides by emitting particles and EM radiation.
- Radioactivity is the emission of particles and EM radiation from an unstable nuclide.
- The time scale for the decay processes can range from microseconds to billions of years.

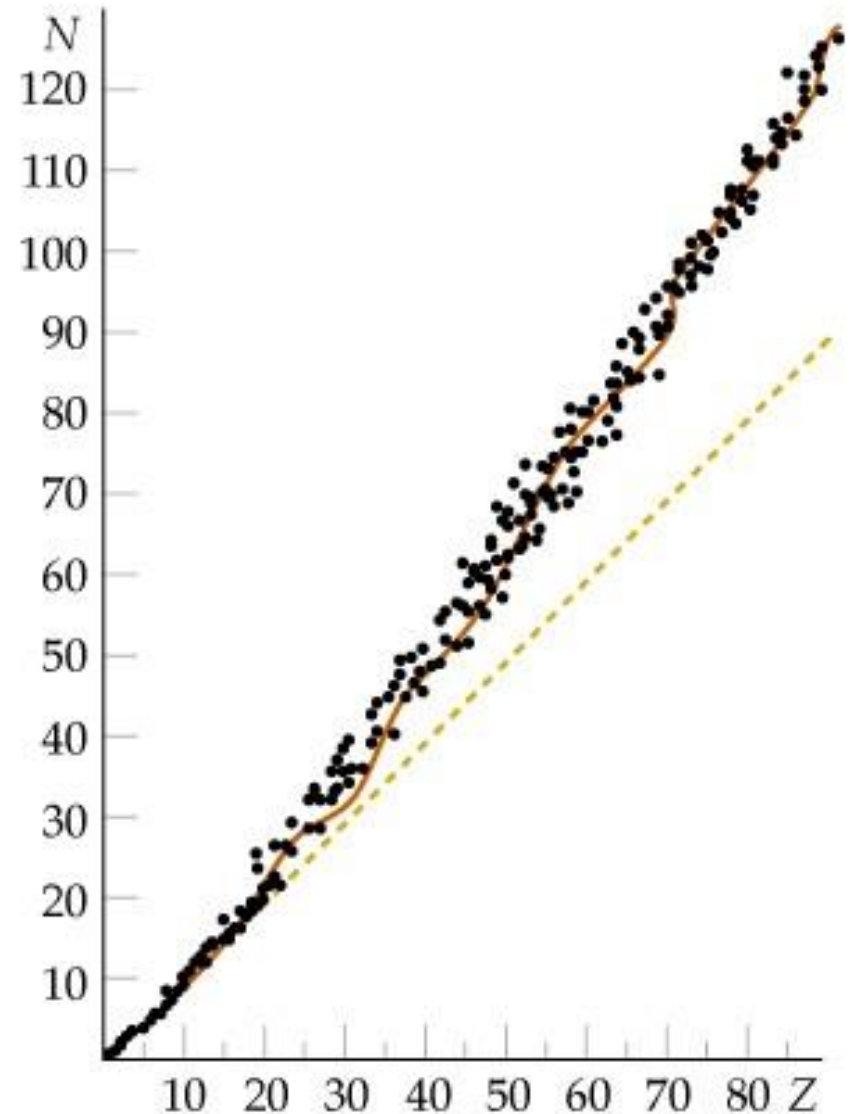
Nuclear Stability

- The stable nuclides are shown as dots.
- In stable nuclides, the number of neutrons exceeds the number of protons by an amount that increases with the atomic number Z .
- For low mass numbers, the numbers of protons and neutrons is about equal.



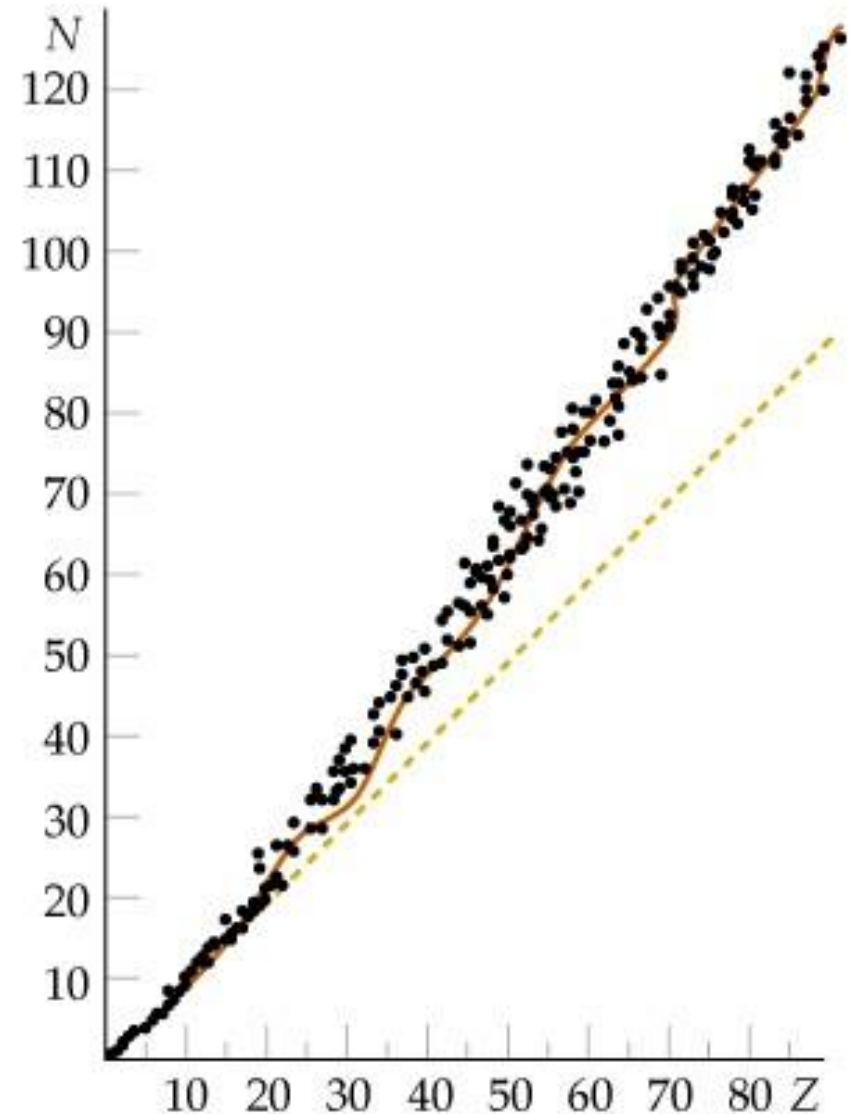
Nuclear Stability

- The ratio N/Z increases gradually with mass, up to about 1.6 at large mass numbers because of the increasing influence of the electrical repulsion of the protons.
- Points to the right of the stability region represent nuclides that have too many protons to neutrons to be stable.



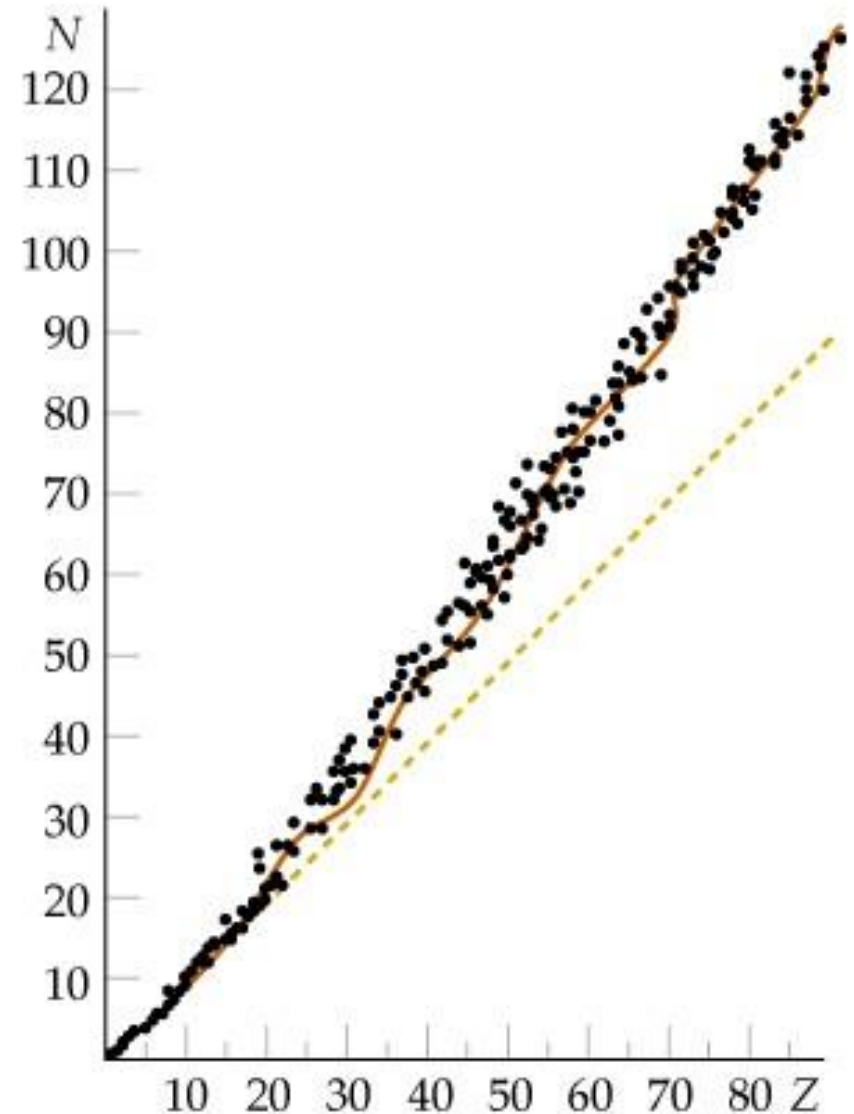
Nuclear Stability

- Repulsion wins and the nucleus comes apart.
- To the left are nuclides with too many neutrons to protons.
- The energy associated with the neutrons is out of balance with the energy associated with the protons and the nuclides decay in a process that converts neutrons to protons.



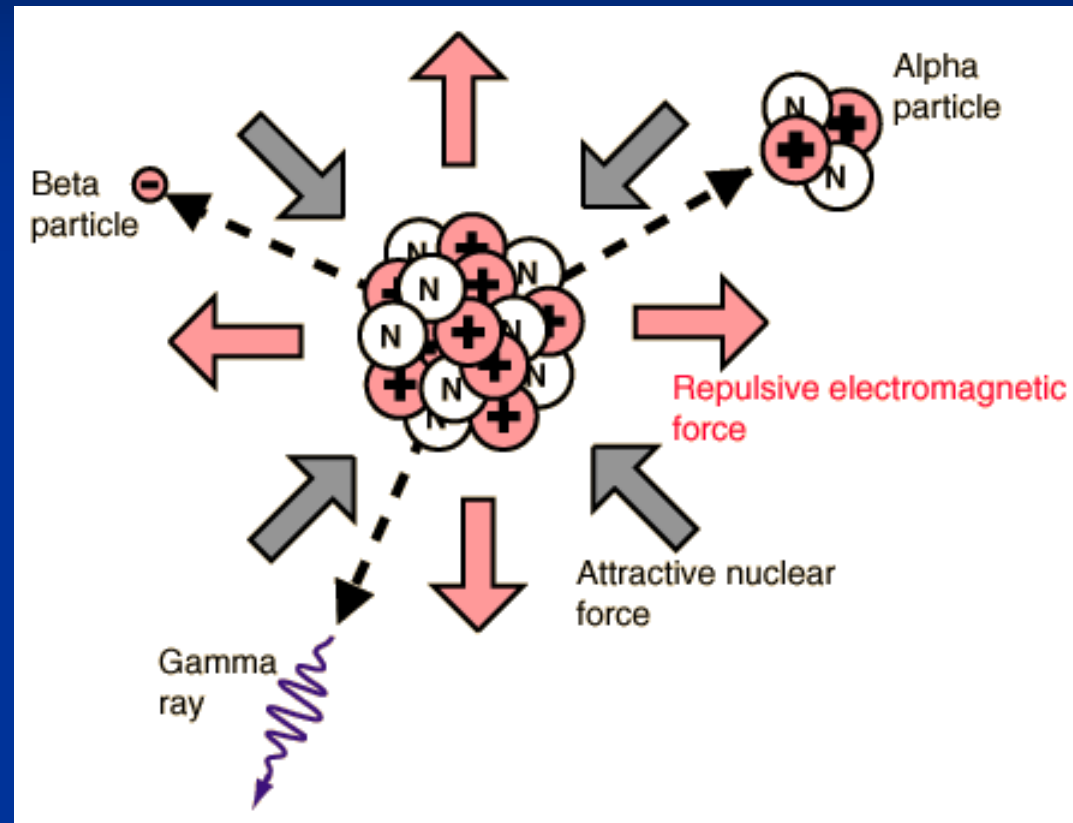
Nuclear Stability

- No nuclide with with a mass > 209 or atomic number > 83 is stable.
- A nucleus is unstable if it is too big.
- Nearly 90% of the 2500 known nuclides are radioactive and decay into other nuclides.



Radioactivity

- The conflict between the electromagnetic force of repulsion and the strong nuclear force results in the instability that causes nuclides to be unstable and emit some kind of radiation.



Alpha (α) Decay

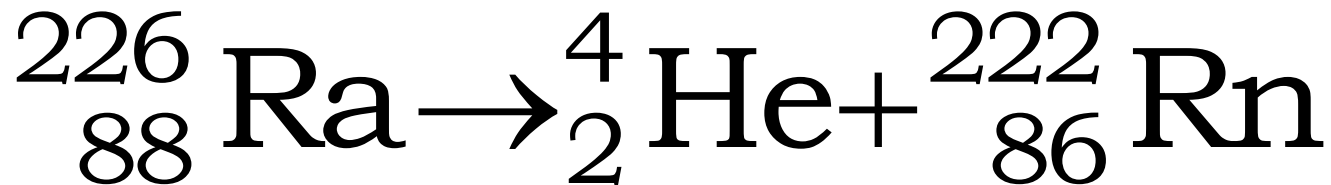
- An alpha particle is a ${}^4_2\text{He}$ nucleus, 2 protons and 2 neutrons.
- Alpha emissions occur primarily with nuclei that are too large to be stable.
- When a nucleus emits an alpha particle, its mass number decreases by 4 and its atomic number decreases by 2.
- Because of its very large mass (more than 7000 times the mass of the beta particle) and its charge, it has a very short range.

Alpha (α) Decay

- It is not suitable for radiation therapy since its range is less than a tenth of a millimeter inside the body.
- Its main radiation hazard comes when it is ingested into the body; it has great destructive power within its short range.
- In contact with fast-growing membranes and living cells, it is positioned for maximum damage.

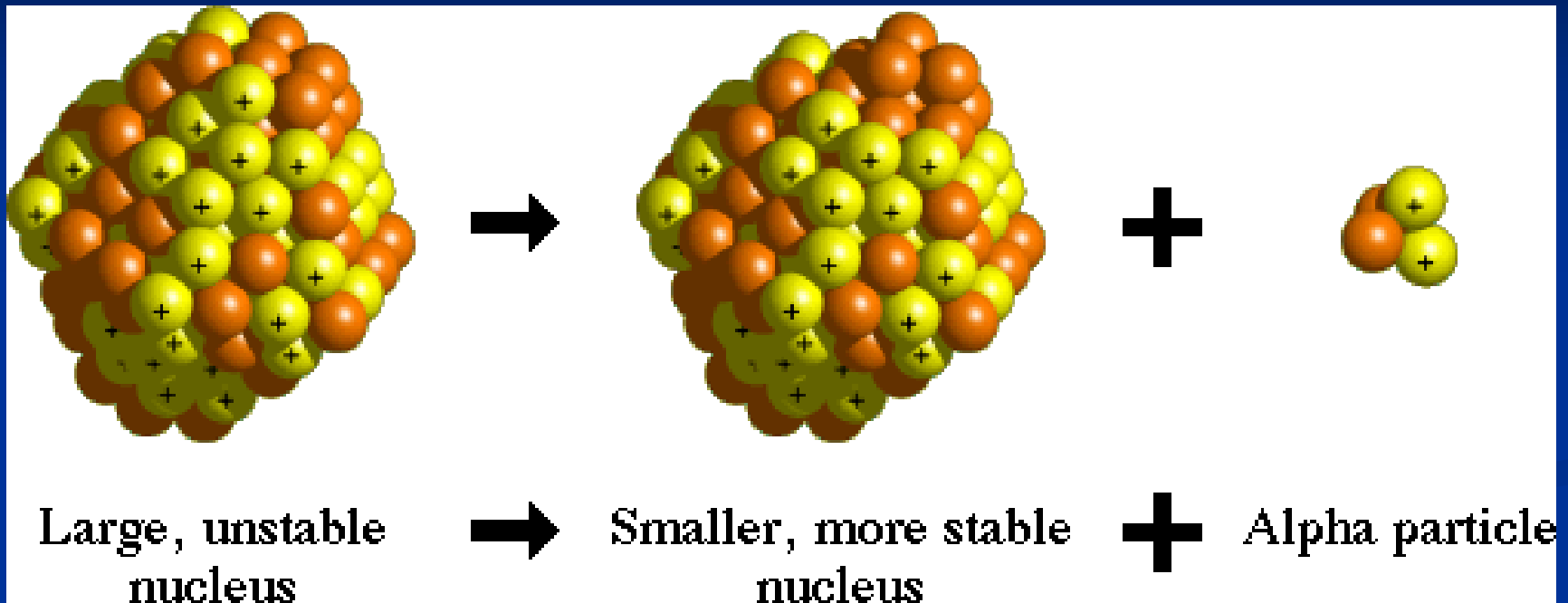
Alpha (α) Decay

- Example: alpha decay of ${}^{226}_{88}\text{Ra}$



- Alpha decay is possible whenever the mass of the original neutral atom is greater than the sum of the masses of the final neutral atom and the neutral ${}^4_2\text{He}$ atom.

Alpha Decay



This is the preferred decay mode of nuclei heavier than ^{209}Bi with a proton/neutron ratio along the valley of stability

Beta Decay

- There are three types of beta decay:

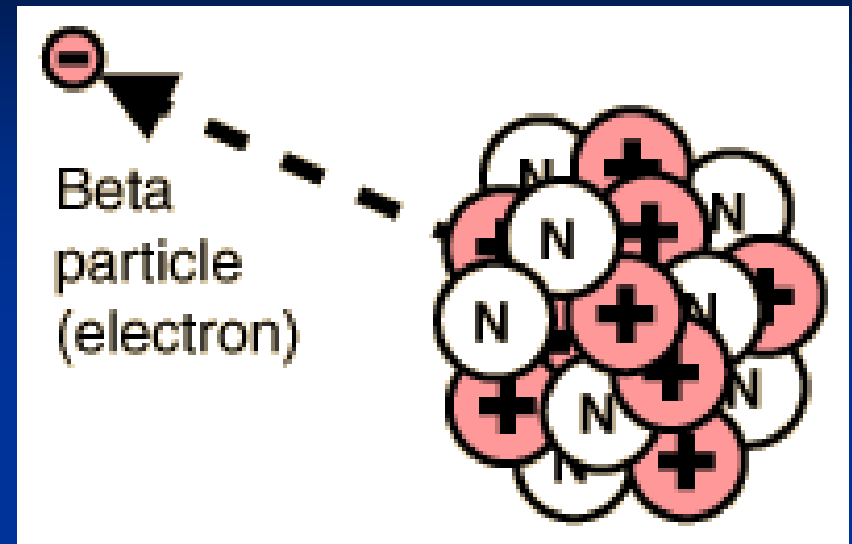
- Beta-minus

- Beta-plus

- Electron capture

- Beta particles are just electrons from the nucleus.

- The high energy electrons have greater range of penetration than alpha particles, but still much less than gamma radiation.



Beta Minus (β^-) Decay

- A beta-minus β^- particle is an electron.
- It's not obvious how a nucleus can emit an electron if there aren't any electrons in the nucleus.
- Emission of a β^- involves the transformation of a neutron into a proton, an electron and an anti-neutrino.
- The anti-neutrino shares the energy and momentum of the decay.

Neutrinos

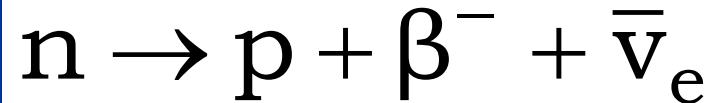
- 1930 proposed a particle called a neutrino which could carry away missing energy and momentum.
- A neutrino has no charge and no mass and was not detected until 1953.
- For symmetry reasons, the particle emitted along with the electron from nuclei is called an antineutrino. The emission of a positron is accompanied by a neutrino.

Neutrinos

- Neutrinos are similar to the electron, with one crucial difference: neutrinos do not carry electric charge.
- Because neutrinos are electrically neutral, they are not affected by the electromagnetic forces which act on electrons.
- Neutrinos are affected only by a "weak" sub-atomic force of much shorter range than electromagnetism.
- Neutrinos are not understood very well.
- The symbol for the neutrino is the ν .

Beta Minus (β^-) Decay

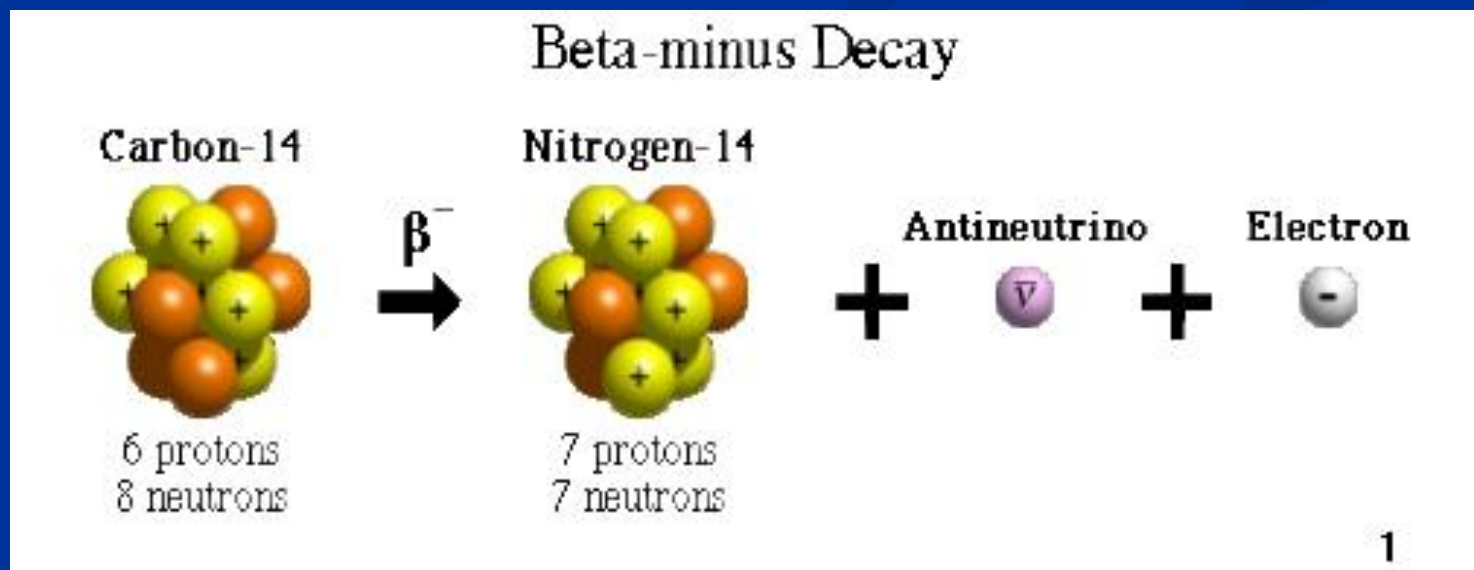
- The anti-neutrino emitted with in β^- decay is denoted as $\bar{\nu}_e$.
- The basic process of β^- decay is:



- β^- decay usually occurs with nuclides in which the neutron to proton ratio N/Z is too large for stability.

Beta Minus (β^-) Decay

- In β^- decay, the mass number remains the same and the atomic number increases by 1.
- β^- decay can occur whenever the neutral atomic mass of the original atom is larger than that of the final atom.



Beta Plus (β^+) Decay

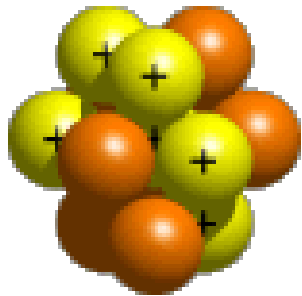
- Nuclides for which the neutron to proton ratio is too small for stability can emit a positron.
- The positron is a positively charged electron (the electron's anti-particle).
- The positron is accompanied by a neutrino, a particle with no mass and no charge.
- Positrons are emitted with the same kind of energy as electrons in β^- decay because of the emission of the neutrino.

Beta Plus (β^+) Decay

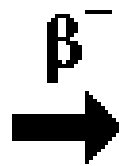
- The basic process: $p \rightarrow n + \beta^+ + \nu_e$
- β^+ is the positron; ν_e is the electron neutrino.
- β^+ decay can occur whenever the neutral atomic mass of the original atom is at least two electron masses larger than that of the final atom.

Beta-minus Decay

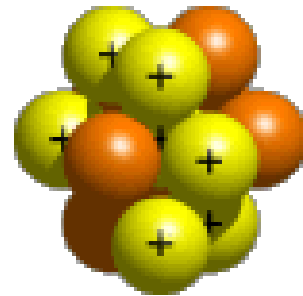
Carbon-14



6 protons
8 neutrons



Nitrogen-14

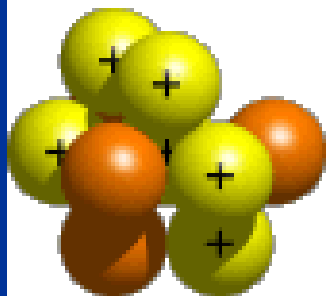


7 protons
7 neutrons



Beta-plus Decay

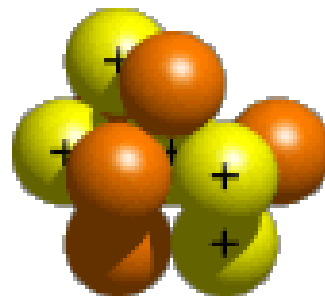
Carbon-10



6 protons
4 neutrons



Boron-10



5 protons
5 neutrons

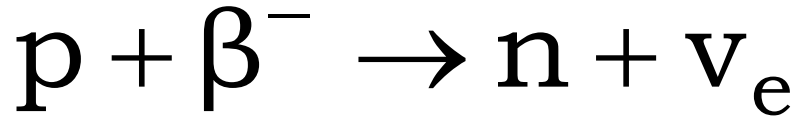


Electron Capture

- A parent nucleus may capture one of its orbital electrons. The electron combines with a proton in the nucleus to form a neutron and emit a neutrino.
- This is a process which competes with positron emission and has the same effect on the atomic number.
- Most commonly, it is a K-shell electron (inner shell electron) which is captured, and this is referred to as K-capture.

Electron Capture

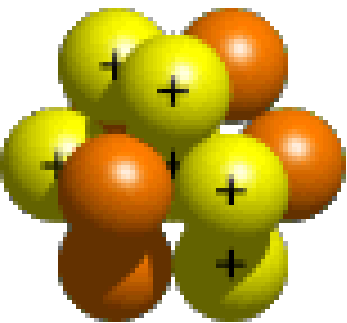
- The basic process:



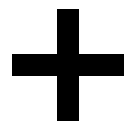
- Electron capture can occur whenever the neutral atomic mass of the original atom is larger than that of the final atom.
- In β^{+} decay and electron capture, the number of neutrons increases by 1 and the atomic number decreases by 1 as the neutron-proton ratio increases toward a more stable value.

Electron Capture

Carbon-11



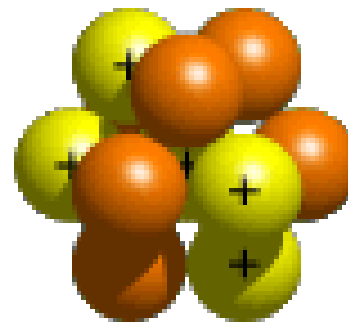
6 protons
5 neutrons



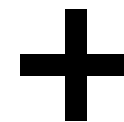
Electron



Boron-11



5 protons
6 neutrons



Neutrino

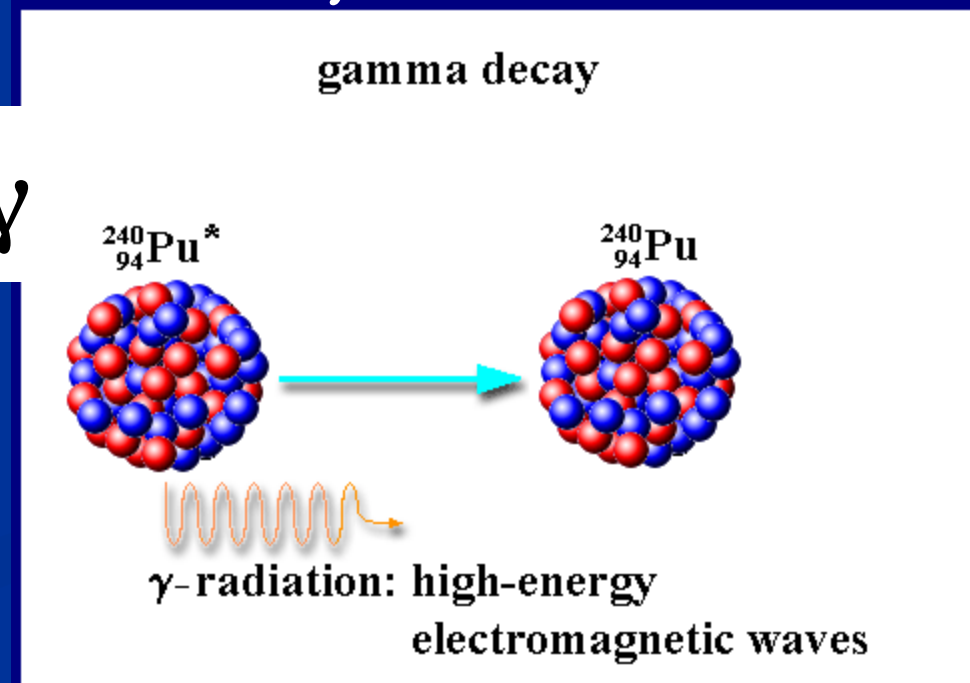
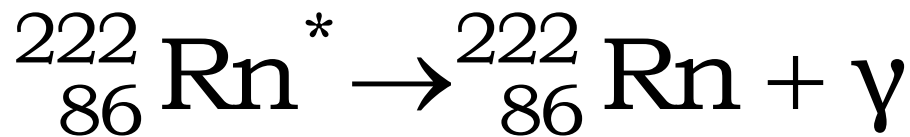


Gamma Decay

- A typical nucleus has a set of allowed energy levels, including a ground state and several excited states.
- When a nucleus is placed in an excited state, either by bombardment with high-energy particles or by radioactive transformation, it can decay to the ground state by emission of one or more photons called gamma rays (γ).

Gamma Decay

- In gamma decay, the element does not change; the nucleus goes from an excited state to a less excited state.
- A nucleus in an excited state is indicated with an asterisk (*) next to the element symbol.



Various Decay Pathways

Alpha decay	${}^A_Z X \rightarrow {}^{A-4}_{Z-2} X + {}^4_2 \text{He}$
Negative beta decay	${}^A_Z X \rightarrow {}^A_{Z+1} X + \beta^- + \bar{\nu}$
Positive beta decay	${}^A_Z X \rightarrow {}^A_{Z-1} X + \beta^+ + \nu$
Electron capture	${}^A_Z X + {}^0_{-1} e \rightarrow {}^A_{Z-1} X + \nu$
Gamma decay	${}^A_Z X^* \rightarrow {}^A_Z X + \gamma$

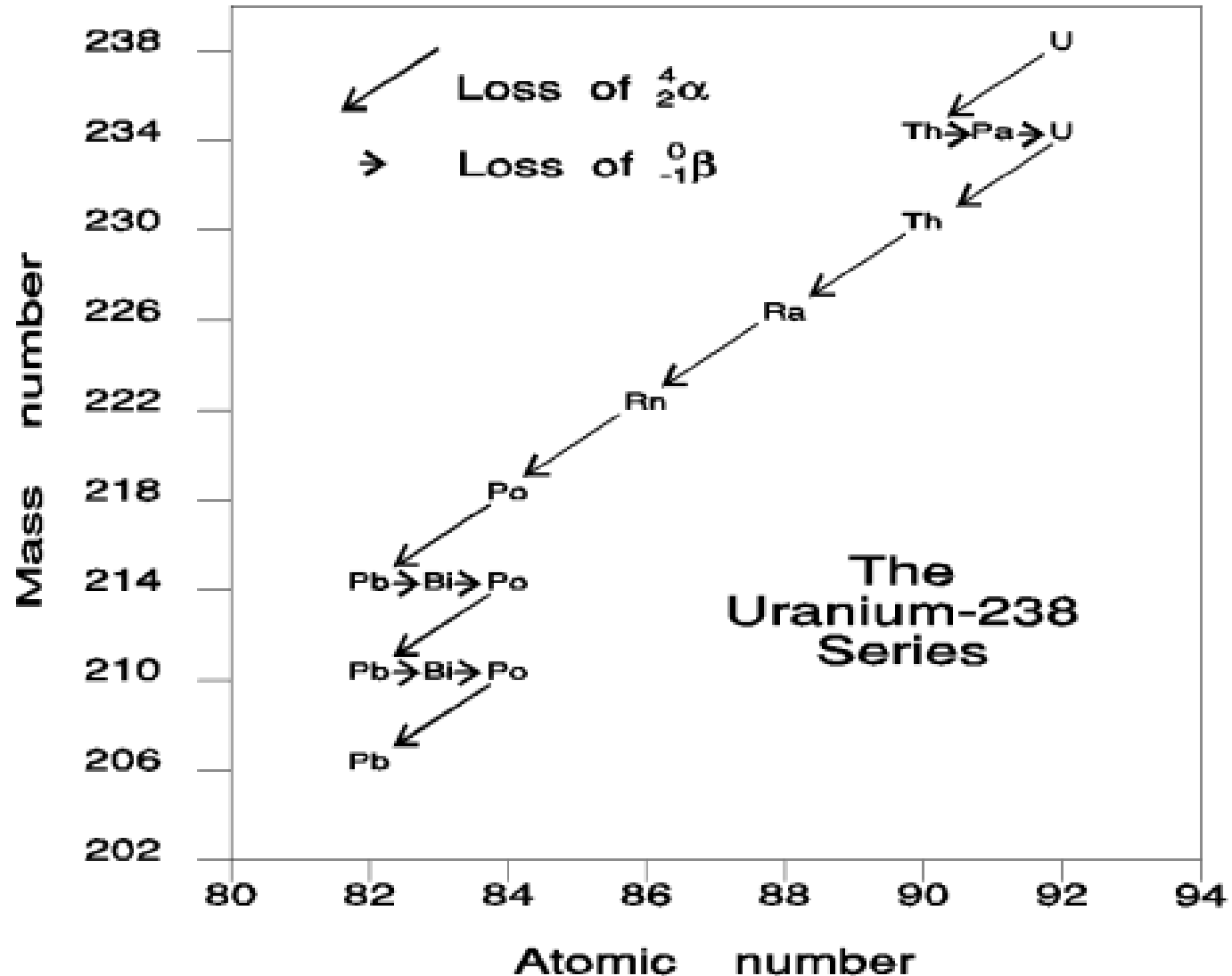
Natural Radioactivity

- The decaying nucleus is called the parent nucleus; the resulting nucleus is called the daughter nucleus.
- When a radioactive nucleus decays, the daughter nucleus may also be unstable.
- When this occurs, a series of successive decays occurs until a stable nuclide is reached.
- The most abundant radioactive nuclide found on Earth is U-238, which undergoes a series of 14 decays, including 8 alpha emissions and 6 beta emissions to reach the stable isotope Pb-206.

Figure . Chart showing the decay chain of the uranium and thorium series isotopes and the half-lives of each isotope (in green). Alpha decays are shown by the vertical arrows (↓) and beta decays by the diagonal arrows (↗).

Atomic Number	Element	U-235 Series				
92	Uranium	U-235 7.04 × 10 ⁸ yrs				
91	Protactinium	↓	Pa-231 3.25 × 10 ⁴ yrs			
90	Thorium	Th-231 25.5 hrs	↓	Th-227 18.7 days		
89	Actinium		Ac-227 21.8 yrs	↓		
88	Radium			Ra-223 11.4 days		
87	Francium			↓		
86	Radon			Rn-219 3.96 sec		
85	Astatine			↓		
84	Polonium			Po-215 1.78 × 10 ³ sec		Po-211 0.516 sec
83	Bismuth			↓	Bi-211 2.15 min	↓
82	Lead			Pb-211 36.1 min		Pb-207 stable lead (isotope)

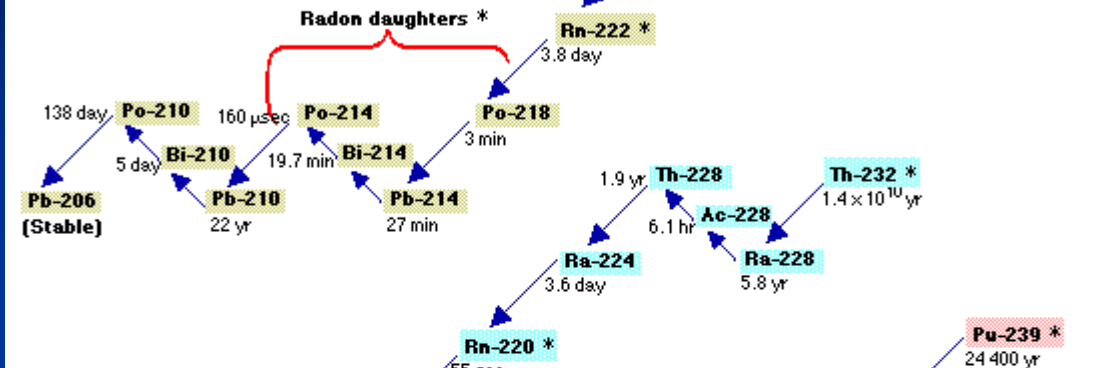
Natural Radioactivity



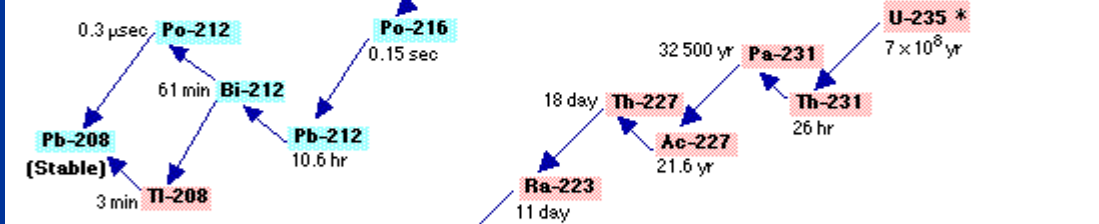
Some radioactive decay series

Showing half lives

Uranium series



Thorium series



Actinium series



= alpha decay
 = beta decay
 Some decays also release gamma radiation.

Notes:

1. In a uranium orebody, the U-238 series represents almost 95% of the radioactivity.
2. The level of radioactivity of an isotope is inversely proportional to its half life. The shorter-lived each kind of radioisotope, the more radiation it emits per unit mass. Th-232, U-235 and U-238 are thus virtually stable.

* Specifically mentioned in text or footnote.

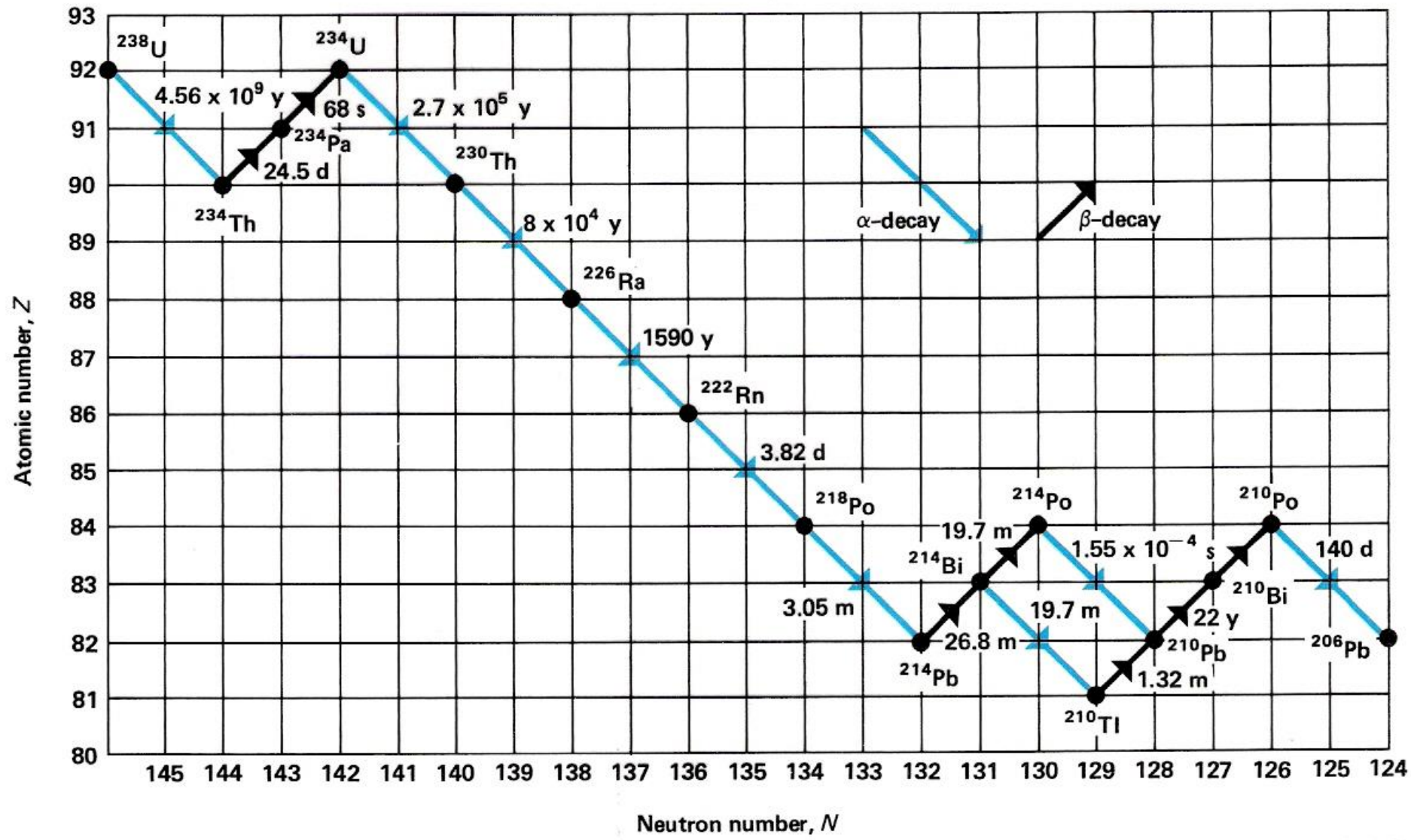
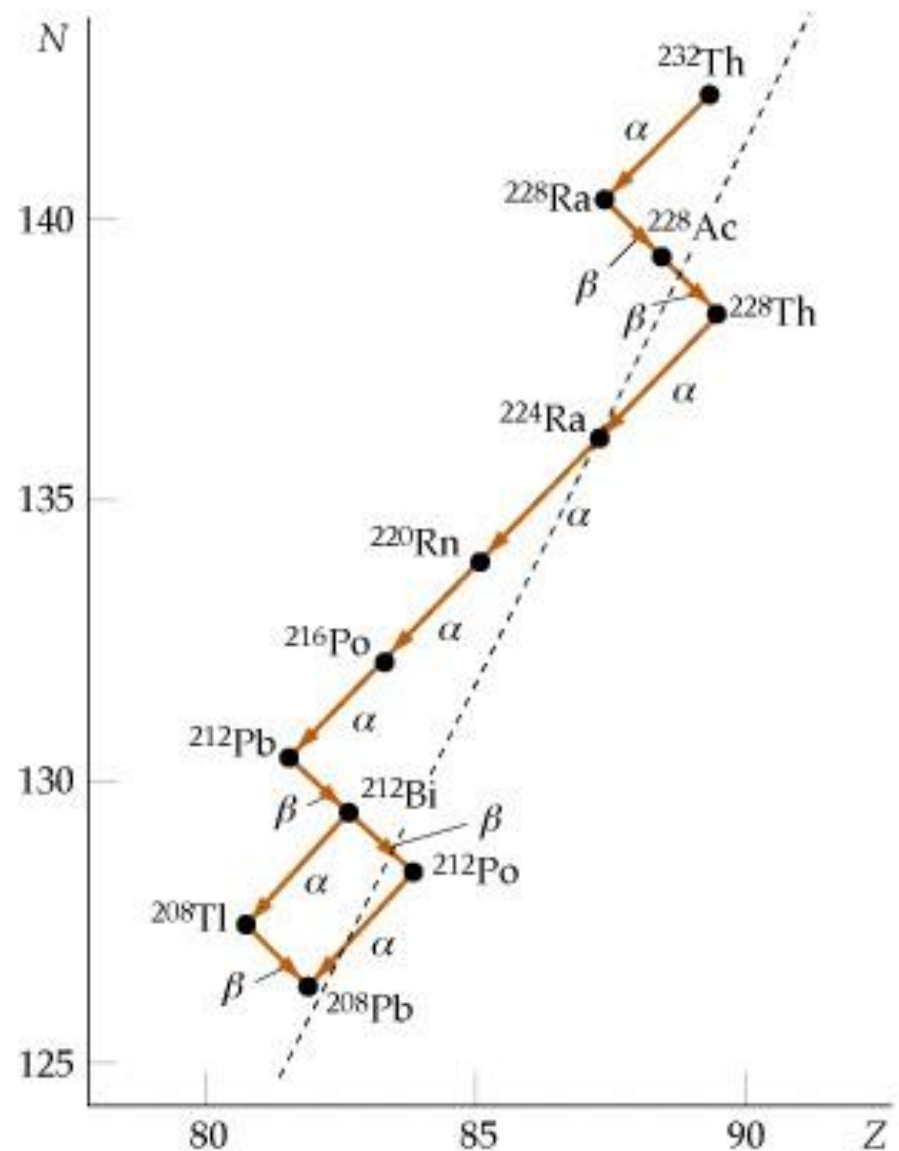


Figure MD 24.5

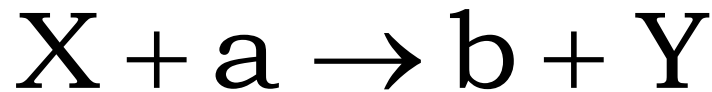
Natural Radioactivity

- Another common decay series is the decay of Th-232 to Pb-208.
- Each decay series ends with lead Pb, atomic number 82 and mass less than 209 (remember, no nuclide with with a mass > 209 or atomic number > 83 is stable).










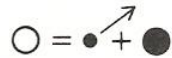





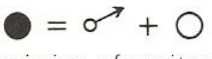

Nuclear Equation Shorthand

- It is possible to change the structure of nuclei by bombarding them with energetic particles.
- Such collisions, which change the identity of the target nuclei, are called nuclear reactions.
- Consider a reaction in which a target nucleus X is bombarded by a particle a , resulting in a nucleus Y and a particle b .



- This reaction can be written in shorthand form:



Type of Decay	Parent nucleus	Decay event	Daughter nucleus	Reason for instability
Gamma decay		 Emission of gamma ray reduces energy of nucleus		Nucleus has excess energy
Alpha decay		 Emission of alpha particle reduces size of nucleus		Nucleus is too large
Beta decay		 Emission of electron by nuclear neutron changes it to a proton		Nucleus has too many neutrons relative to number of protons
Electron capture		 Capture of electron by nuclear proton changes it to a neutron		Nucleus has too many protons relative to number of neutrons
Positron emission		 Emission of positron by nuclear proton changes it to a neutron		Nucleus has too many protons relative to number of neutrons

● Proton (charge = +e)

○ Neutron (charge = 0)

● Electron (charge = -e)

○ Positron (charge = +e)