Nuclear Stability and Decay

31.2: The Strong Nuclear Force and the Stability of the Nucleus

Concept Summary

"The strong nuclear force is the force of attraction between nucleons (protons and neutrons) and is one of the three fundamental forces of nature. This force balances the electrostatic force of repulsion between protons and holds the nucleus together. The strong nuclear force has a very short range of action and is almost independent of electric charge."

Notes

- The strong nuclear force is one of 3 fundamental forces along with the electroweak force and the gravitational force
- The strong nuclear force holds the nucleus together, opposing the force of two extremely close protons repelling each other
- It is almost independent of electric charge
- At a given distance nearly the same nuclear force of attraction exists between 2 protons, 2 neutrons, or one of each
- Extremely short range of action compared to the electric force(falls off gradually with distance), very strong at $10^{-15}m$ and near zero at larger distance
- For a nucleus to be stable the electrostatic repulsion between protons has to be balanced by the strong nuclear force, since one proton can repel all other protons in the nucleus(due to the large range of action of the electrostatic force) and a proton or neutron can only attract it's nearest neighbors(due to the short range of action of the strong nuclear force) as the number of protons in the nucleus Z increases the number of neutrons N has to increase even more(to maintain stability)

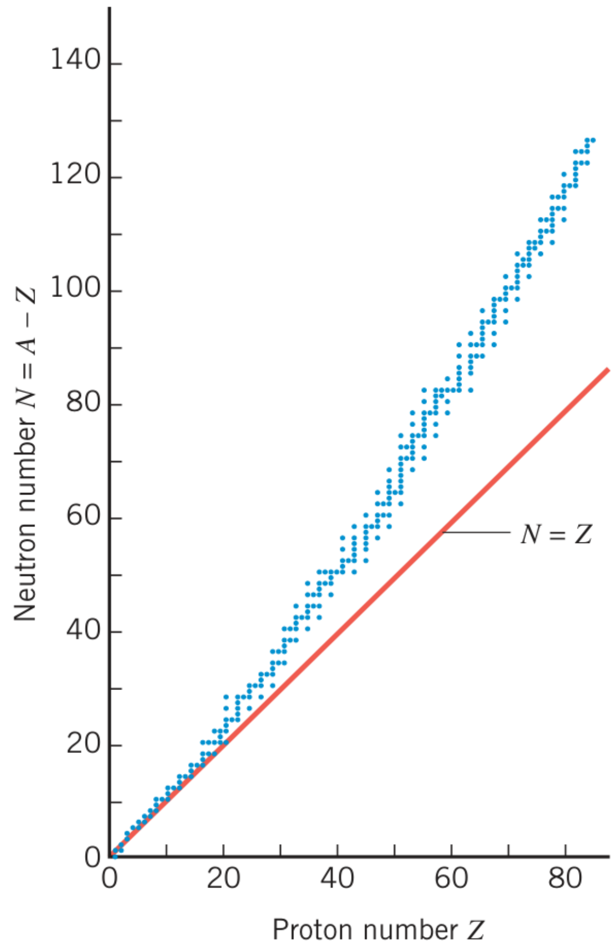

Figure 31.2 With few exceptions, the naturally occurring stable nuclei have a number N of neutrons that equals or exceeds the number Z of protons. Each dot in this plot represents a stable nucleus.

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– As the number of protons in the nucleus Z increases there is a point at which additional neutrons can no longer balance the forces, the limited range of action of the strong nuclear force prevents the additional neutrons from balancing out the longer range electric repulsion of the additional protons

– The largest known stable nucleus(bismuth) contains 83 protons and 126 neutrons

– All nuclei with more than 83 protons(such as uranium) are not stable and spontaneously break apart or rearrange their internal structure, this process is known as radioactivity(31.4

31.4: Radioactivity

Concept Summary

"Unstable nuclei spontaneously decay by breaking apart or rearranging their internal structure in a process called radioactivity. Naturally occurring radioactivity produces α, β, and γ rays. α rays consist of positively charged particles, each particle being the $^{4}_{2}\mathrm{He}$ nucleus of helium. The general form of decay is:

$$\underset{\text{Parent Nucleus}}{{}^{A}_{Z}P} \quad \rightarrow \quad \underset{\text{Daughter Nucleus}}{{}^{A-4}_{Z-2}D} \quad + \quad \underset{\alpha\text{ particle(helium nucleus)}}{{}^{A}_{Z}He}$$

The most common kind of β ray consists of negatively charged particles, or β^{-} particles, which are electrons. The general form of β^{-} decay is:

$$\underset{\text{Parent Nucleus}}{{}^{A}_{Z}P} \quad \rightarrow \quad \underset{\text{Daughter Nucleus}}{{}^{A}_{Z+1}D} \quad + \quad \underset{\beta^{-1}\text{ particle(electron)}}{{}^{0}_{-1}e}$$

β^{+} decay produces another kind of β ray, which consists of positively charged particles, or β^{+} particles. A β^{+} particle, also called a positron, has the same mass as an electron but carries a charge of $+e$ instead of $-e$.

If a radioactive parent nucleus disintegrates into a daughter nucleus that has a different atomic number, as occurs in α and β decay, one element has been converted into another element, the conversion being referred to as a transmutation.

γ rays are high-energy photons emitted by a radioactive nucleus. The general form for γ decay is:

$$\underset{\text{Excited energy state}}{{}^{A}_{Z}P^{*}} \quad \rightarrow \quad \underset{\text{Lower energy state}}{{}^{A}_{Z}P} \quad + \quad \underset{\gamma\text{ ray}}{\gamma}$$

γ decay does not cause a transmutation of one element into another.

Notes

Basic Concepts

- when an unstable/radioactive nucleus disintegrates, particles and/or high-energy photons are released, these particles and photons are collectively called "rays"
- there are 3 types of rays in naturally occurring radioactivity: α alpha, β beta, and γ gamma, these distinctions indicate the extent of their ability to penetrate matter:
  - α blocked by $\approx 0.01mm$ of lead
  - β blocked by $\approx 0.1mm$ of lead
  - γ blocked by $\approx 100mm$ of lead
- The radioactivity that produces these rays must obey the conservation laws of physics:
  1. Conservation of energy/mass (Sections 6.8 and 28.6)
  2. Conservation of linear momentum (Section 7.2)
  3. Conservation of angular momentum (Section 9.6)
  4. Conservation of electric charge (Section 18.2)
  5. Conservation of nucleon number (Section 31.4)
     - In all radioactive decay processes the number of nucleons(protons and neutrons) stays constant
- The energy, electric charge, linear momentum, angular momentum, and nucleon number that a nucleus must remain unchanged when it disintegrates into nuclear fragments and α, β, and γ rays
- α and β rays are made of charged particles, γ rays are not

α Decay

- when a nucleus disintegrates and produces α rays it is undergoing α decay
- α rays consist of positively charged particles(the ^4_2He nucleus of helium)
- α particle has a charge of $+2e$ and a nucleon number of $A = 4$
- Example of α decay:

$$\underset{\text{Parent nucleus(uranium)}}{^{238}_{92}P} \quad \rightarrow \quad \underset{\text{Daughter nucleus(thorium)}}{^{234}_{90}Th} \quad + \quad \underset{\alpha\text{ particle(helium nucleus)}}{^4_2He}$$

- The original nucleus is called the *parent nucleus*(P), and the nucleus remaining after the disintegration is the *daughter nucleus*(D).
- The parent and daughter nuclei are different, so α decay converts one element into another, in a process called ***transmutation***
- Electric charge is conserved, in the example 90 of the protons end up in the thorium and 2 in the helium
- The number of nucleons is conserved, in the example number of nucleons 238 is the same, 234 going to the thorium and 4 to the helium
- General form for α decay:

$$\underset{\text{Parent Nucleus}}{{}^{A}_{Z}P} \quad \rightarrow \quad \underset{\text{Daughter Nucleus}}{{}^{A-4}_{Z-2}D} \quad + \quad \underset{\alpha\text{ particle(helium nucleus)}}{{}^{A}_{Z}He}$$

- During α decay, energy is also releases, using the same example we can see how energy is released during alpha decay
- Example Continued:
  The atomic mass of uranium ${}^{238}_{92}U$ is $238.0508u$, that of thorium ${}^{234}_{90}Th$ is $234.0436u$