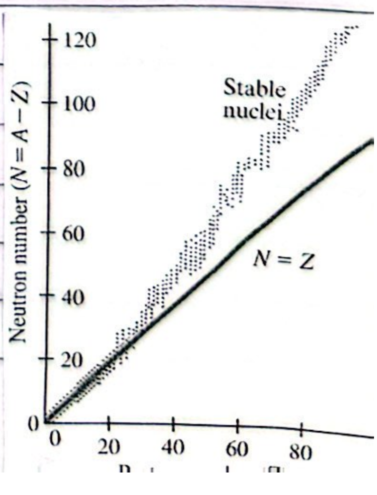
Chap 30
Nuclear physics and Radioactivity

30.1 Structure and properties of the Nucleus

A nucleus is made up of two types of particles

1. A proton, which has a positive charge ($+e$) $= 1.6 \times 10^{-19}$ C, the Same of the charge for electron in magnitude and its mass $m_p = 1.67262 \times 10^{-27}$ Kg
2. A neutron which is electrically neutral ($q = 0$). It's mass $m_n = 1.67493 \times 10^{-27}$ Kg which is very slightly larger than m_p.

- These two Constituents of the nucleus, the proton and neutron are reffered as nucleons
- The atomic number which has the symbol $\boxed{Z}$ which is equal to the number of protons in the nucleus.



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- The atomic mass number or mass number, which has the symbol $\boxed{A}$, which is equal to the number of nucleons (neutrons plus protons). Therefore a nucleus with $\boxed{7}$ protons and $\boxed{8}$ neutrons has $\boxed{Z = 7}$ and $\boxed{A = 15}$, so the number of neutrons N

$$\boxed{N = A - Z}$$

- To specify a given nucleus (nuclide), A special symbol is used which takes the form

$${}^{A}_{Z}X \qquad \text{where} \qquad (30.1)$$

X is the chemical symbol for the element (hydrone H, Oxigen O, Carbon C ...)

A is the atomic mass number and Z is the atomic number. For example

${}^{15}_{7}N$ means nitrogen nucleus with $\boxed{\text{7 protons}}$ and $\boxed{\text{8 neutrons}}$ and some time it's written ${}^{15}N$

in words we say "nitrogen fifteen".

- Nuclei that contain the same number of protons but different numbers of neutrons are called isotopes, thus we have $^{11}_{6}C$, $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$, $^{15}_{6}C$ and $^{16}_{6}C$ are all isotopes of Carbon.

- Natural Abundance (NA) referes to the percentage of the abundance of a certain isotope of a chemical element as naturally found on the earth. For example 98.9% of the Carbon found on earth is $^{12}_{6}C$, and about 1.1% is $^{13}_{6}C$. Also hydrogen has three isotopes 99.99% of natural hydrogen is $^{1}_{1}H$ and the other two isotopes $\boxed{^{2}_{1}H}$ or $^{2}_{1}D$ is called deuterrium, and $\boxed{^{3}_{1}H}$ is called tritium.

- The approximate size of the nuclei (determined by Rutherford is $r \simeq 1.2\times 10^{-15}\,m(A^{\frac{1}{3}})$, that is the volume of it is proportional to A thus $r \simeq 1.2\times10^{-15} m (A^{1/3}) = 1.2$ ft (femtometer) $(A^{1/3})$

$= 1.5$ fermi's $(A^{1/3})$ (30.2)

Example 30.1 Nuclear sizes:

Estimate the diameter of the smallest and largest nuclei (a) $^{1}_{1}H$, $^{238}_{92}U$,?

Solution

(a) $r \simeq 1.2\times10^{-15} A = 1.2\times10^{-15} (1)^{1/3}$ but

the diameter $d = 2r = 2(1.2\times10^{-15} \underbrace{(1)^{1/3}}_{1} = 2.4\times10^{-15}$ m

(b) For Uranium $d = 2.4\times10^{-15}$ m $(238)^{1/3} = 15\times10^{-15}$ m

the range of the diameter of the nuclei is between 2.4 fm to 15 fm.

- Nuclear masses can be specified by unified mass unit (u) which is given by

$$u = 1.66054\times10^{-27} \text{ kg} = 931.5 \text{ MeV}/c^2.$$

- Some of the basic particles, their rest masses are given in table 30.1

30.3 Radioactivity

Some mineral emitted radiation with out any external stimulus. This phenomenon is called radioactivity (some of these mineral or elements are Polonium and Radium and Uranium

- Radioactivity is the result of the disintegration or decay of an unstable nucleus to emit some type of radiation or rays.
- Natural radioactivity is defined as the emitting of radiation by naturally unstable isotopes
- Artificial radioactivity is defined as the emitting of radiation by artificial unstable isotopes produced in the laboratory.

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- There are three types of radiation that emitted by the radioactive element

1. Alpha particles(rays) α ;

i) they are helium nuclei $^{4}_{2}He$.

ii) they are positively charged protons

iii) they have low speed $v = 0.05\,C$

iv) they have greatest ionization by least penetration (1mm of paper)

2. Beta particles(rays) β ;

i) they are negatively charged particles (electrons) e

ii) They have high speed $v \simeq 0.9C$

iii) less ionization and greater penetration (3mm of aluminium (Al).

3. **Gamma particles(rays) γ**

i) They are electromagnetic radiation (waves) of very short wavelength and high frequency

ii) They have no electric charge (neutral)

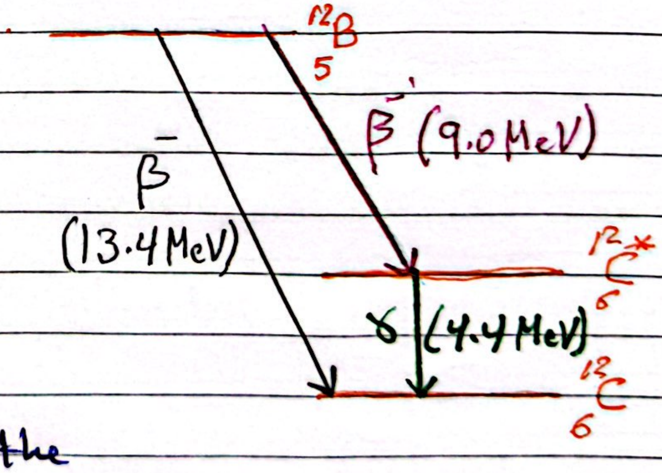
iii) They are the least ionization and the greatest penetration (~ 6cm of lead)

iV) They travel with the speed of light

30.6 Gamma Decay

A nucleus Can be in an excited state, because of a violent Collision with another particle. More Commonly, the nucleus remaining after a previous radiative decay in an excited state. Atypical example is shown in the figure

A Boron $^{12}_{5}B$ nucleus Can decay to Carbon $^{12}_{6}C$ by two ways



1. Decay directly to the ground state of Carbon $^{12}_{6}C$ nucleus by β decay
2. Decay to an excited state of $^{12}_{6}C$ written $^{12}_{6}C^*$ (* means excited state), which itself

decays to the ground state of $^{12}_{6}C$ by the emission of a 4.4 MeV γ ray.

30.8 Half-Life and Rate of Decay

In any radioactive process, not all nuclei in a sample will decay at one time, Rather, they decay one by one over a period of time. This is a random process, but we can determine approximately, on a probabilistic basis how many nuclei in a sample will decay over a given period of time

- **The rate of decay** which is the number of decays per second is given by

$$\frac{\Delta N}{\Delta t} = -\lambda N \quad \text{where} \qquad (30.3)$$

N is the **total number** of the original radioactive nuclei and **λ** is called the **decay constant**

which is a measurable constant and is different for different isotopes. The greater λ, the greater the rate of decay and the isotope is to have more radioactive

Exponential Decay

Equation (30.3) can be written in an exponential form as

$$N = N_0 e^{-\lambda t} \qquad (30.4)$$

where N_0 is the number of parent (original) nuclei at $t=0$, N is the number of remaining nuclei after a time t. e is the natural exponential whose value 2.718..

that is the number of parent nuclei decreases exponentially with time.

- Equation (30.4) is called $\boxed{\text{radioactive decay law}}$

- The decay rate $R = \left|\frac{\Delta N}{\Delta t}\right|$ is also called the activity of the sample. which is always positive

This is true for the magnitude of R, so the activity of a pure sample at time t is

$$R = \left|\frac{\Delta N}{\Delta t}\right| = R_0 e^{-\lambda t} \quad (30-5)$$

where $R_0 = \left|\frac{\Delta N}{\Delta t}\right|_0$ is the activity at $t=0$.

- Equation (30-5) is also called the radioactive decay law as Eq. (30-4).

Half-Life

- The rate of decay of any isotope is often specified by given the "half-life" rather than the decay constant λ.
- The half-life of an isotope is defined as the time it takes for half of the original Number of parent nuclei to decay.

For example, the half-life of $^{14}_{6}C$ is about 5730 years (yr). If a piece of word contains 1×10^{22} nuclei of $^{14}_{6}C$, then 5730 yr later, it will have half the 1×10^{22} nuclei that is only 0.5×10^{22} nuclei. After another 5730 yr it will have 0.25×10^{22} nuclei and so on.

as in the figure below

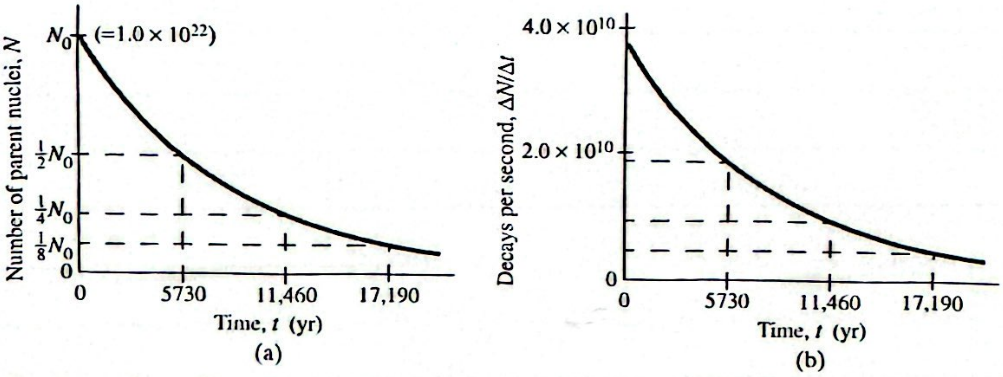


FIGURE 30–10 (a) The number N of parent nuclei in a given sample of $^{14}_{6}C$ decreases exponentially. We assume a sample that has $N_0 = 1.00 \times 10^{22}$ nuclei. (b) The number of decays per second also decreases exponentially. The half-life of $^{14}_{6}C$ is 5730 yr, which means that the number of parent nuclei, N, and the rate of decay, $\Delta N/\Delta t$, decrease by half every 5730 yr.

- The half-lives for radioactive isotopes vary from very short ($\approx 10^{-22}$ s) to very long (10^{23} yr $\geq 10^{30}$ s).
- The half-life is denoted by $T_{1/2}$

- The half-life ($T_{1/2}$) has an inverse relation with the decay constant λ which is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \qquad (30-6)$$

$\boxed{\text{Example 30-9}}$ Sample activity

The isotope $^{14}_{6}C$ has a half-life of 5730 yr. If a sample contains 1×10^{22} nuclei what is the activity of the sample.?

Solution

The decay constant λ can be calculated using equation (30-6)

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(5730\,\text{yr})(3.156 \times 10^{7}\,\text{s/yr})}$$

$= 3.83 \times 10^{-12}\,s^{-1}$, then from eq. (30-5)

$$R = \left|\frac{\Delta N}{\Delta t}\right| = \lambda N = (3.83 \times 10^{-12}\,s^{-1})(1 \times 10^{22})$$

$= 3.83 \times 10^{10}$ decays/s

So if we draw the activity R or the decay rate we get an exponential decay curve as for N

Note: the unit for activity is decays/s or s^{-1} which is called the **becquerel**

$1\ Bq = 1\ \text{decay}/s$

Example 30-11 A Sample of radioactive $^{13}_{7}N$

A laboratory has $1.49\ \mu g$ of pure $^{13}_{7}N$, which has a half-life of $10\ min = 600\ s$.

(a) How many nuclei are present initially

Solution:

The atomic mass $A = 13$, so $13\ g$ will contains 6.02×10^{23} nuclei (Avogadro's number) then

$13\ g$ contains 6.02×10^{23} nuclei

$1.49 \times 10^{-6}\ g$ contains N_0

$$N_0 = \frac{6.02 \times 10^{23} \times 1.49 \times 10^{-6}}{13} = 6.9 \times 10^{16} \text{ nuclei}$$

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(b) What is the rate of decay (activity) R initially

Solution $R_0 = \left|\frac{\Delta N}{\Delta t}\right|_0 = \lambda N_0$

but $\lambda = 0.693/T_{1/2} = \frac{0.693}{600\,s} = 1.155\times10^{-3}\,s^{-1}$

$\Rightarrow R_0 = \lambda N_0 = (1.155\times10^{-3}\,s^{-1})(6.9\times10^{16})$.

$= 7.97\times10^{13}$ decays/s (s^{-1})

(c) What is the activity after 1 hr?

Solution:

The activity at any time $R = R_0 e^{-\lambda t}$

$t = 1\,hr = 60\times60\,s = 3600\,s \Rightarrow$

$R = (7.97\times10^{13}\,s^{-1})(e^{-(1.155\times10^{-3}\,s^{-1})(3600\,s)}$

$= 1.25\times10^{12}\,s^{-1}$

(d) After how long will the activity drop to less than $1\,s^{-1}$?

Solution:

We have $R = R_0 e^{-\lambda t} \Rightarrow e^{-\lambda t} = \frac{R}{R_0}$

$= \frac{1\,s^{-1}}{7.97\times10^{13}\,s^{-1}} = 1.25\times10^{-14} \Rightarrow$

$t = -\frac{\ln(1.25\times10^{-14})}{\lambda} = -\frac{-32}{1.155\times10^{-3}\,s^{-1}} = 2.77\times10^{4}\,s$

$= 7.7$ h.