Chapter 12

Nuclear Physics

12.0 Introduction

Electron was discovered by J. J. Thomson in 1897. In 1911 Ernest Rutherford proposed that positive charge of the atom is densely concentrated at the center of the atom forming its nucleus and that nucleus is responsible for most of the mass of the atom. This claim was based on the experiment suggested by him and carried out his collaborators, Hans Geiger (of Geiger counter frame) and his 20 years old student Ernest Marsden.

During Rutherford’s time frame, it was also known that certain element called radioactive transforms into other element spontaneously by emitting particles in the process. One such element is Radon \( _{86}^{222}\text{Rn} \) that emit alpha \( \alpha \) particle with energy of about 5.5MeV and transforms into polonium \( _{84}^{210}\text{Po} \). Today we know this particle is the nuclei of helium atom.

12.1 Nuclear Properties

The primarily interest in the properties of atomic nuclei as a specified nuclear species rather than as parts of atoms called these particles as nuclides.

12.1.1 Nuclear Terminology

Nuclei are made up of protons and neutrons. The number of protons in a nucleus called atomic number or proton number is represented by the symbol \( Z \). The number of neutron or neutron number is represented by the symbol \( N \). Thus, the total number of protons and neutrons in a nucleus is called mass number \( A \), which is

\[
A = Z + N
\]  

(12.1)

Neutrons and protons are collectively called nucleons.
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Nuclides with same atomic number $Z$ but different neutron number $N$ are called *isotopes*. The element gold $\text{Au}$ has atomic number 79. It has 32 isotopes range from $^{172}\text{Au}$ to $^{204}\text{Au}$ and only $^{197}\text{Au}$ is stable. The remaining 31 are radioactive. Such radionuclide undergoes decay or disintegration by emitting a particle and thereby transforming to a different nuclide.

12.1.2 Organizing the Nuclides

The neutral atoms of all isotopes of an element have same number of electrons and same chemical properties, and they are fit into same box in period table. The nuclear properties of the isotopes of a given element are very different. Thus, the periodic table is of limited use to nuclear physicist, nuclear chemist, or nuclear engineer.

Nuclodic chart like the one shown in Fig. 12.1 is plot of proton number $Z$ with neutron number $N$ for all elements. The stable green color nuclides are laid in the center of the band. The unstable radioactive nuclides are laid at the either side of the green stable nuclides. Note also that the light stable nuclides are laid closed to the $Z = N$ line and for atomic number $Z$ greater than 83, no nuclide is stable.

![Figure 12.1: A nuclidic chart for all isotopes of all elements](image)

Nuclidic chart is also available as wall chart, in which each small box on the chart filled with data about the nuclide it represent. An enlarge portion of the
chart is shown in Fig. 12.2. The green box represents stable nuclides, while the beige color box shows unstable radioactive nuclides. The percentage number in the green box is the relative abundance found in Earth. The time shown in the beige box is the half-life of the radioactive nuclide. An isobar is a line showing nuclides of same mass number such as \( A = 198 \) in this chart.

![Chart showing nuclidic wall chart](image)

**Figure 12.2:** An enlarge portion of nuclidic wall chart

Carl Friedrich Freiherr von Weizsäcker was a German physicist and philosopher. He stated the mass of a nucleus in his Weizsäcker’s formula, which is

\[
M(Z, A) = Z(m_p + m_e) + (A - Z)m_n - \frac{a_p A}{c^2} + \frac{a_c A^{2/3}}{c^2} + a_{\Sigma} \frac{Z(Z-1)}{A^{1/3} c^2} + a_{\lambda} \left(\frac{A - 2Z}{A c^2}\right)^2 + a_{\pi} \frac{A^{1/3}}{A c^2}
\]

\(12.2\)
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Third term is volume term, fourth term is surface term, fifth term is coulomb term, sixth term is asymmetry term, and seventh term is pair term. \( a_V = 15.75 \text{MeV/c}^2 \), \( a_S = 17.80 \text{MeV/c}^2 \), \( a_C = 0.7100 \text{MeV/c}^2 \), \( a_A = 23.69 \text{MeV/c}^2 \), and \( a_P = 39.00 \text{MeV} \). The term \( \frac{a_P}{A^{4/3}c^2} \) is positive if both \( A \) and \( Z \) are even for a nucleus, which has more binding energy, negative if both \( A \) and \( Z \) are odd, which has less binding energy, and otherwise equal to zero. One can see that the mass depends on atomic number \( Z \) and number of neutron \( N \) non-linearly, even for a constant mass number. For odd-even and even-odd nuclei, \( \frac{a_P}{A^{4/3}c^2} \) is equal to zero and the mass dependence on \( Z \) is convex. This explains why beta decay is energetically favorable for neutron rich nuclides and positron decay is favorable for strongly neutron-deficient nuclides.

For even-even nuclei, which has either strong neutron excess or neutron deficiency has higher binding energy than their odd-odd isobar neighbors. It implies that even-even nuclei are relatively lighter and more stable. The difference is especially strong for small \( A \). This effect is also predicted qualitatively by other nuclear models and has important consequences. The expression \( a_V A - a_S A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} \pm \frac{a_P}{A^{4/3}} \) is called the binding energy equation, which defined by the Liquid-Drop Model. This model was first proposed in 1928 by the Russian physicist George Gamov and later on by Niels Bohr. The individual nucleon is analogous to molecule of liquid held together by a short range interaction and surface tension effect.

Based on the mass equation, the minimum atomic number \( Z \) for a given mass is the differentiation of equation (12.2) and equated zero, which is

\[
Z_{\text{min}} = \frac{(m_n - m_p - m_e)c^2 + a_A}{2a_cA^{-1/3} + 2a_AA^{-1}} \quad (12.3)
\]

**Example 12.1**
What should the element stable in isobars 97?

**Solution**
Using equation (12.2), which is \( Z_{\text{min}} = \frac{(m_n - m_p - m_e)c^2 + a_A}{2a_cA^{-1/3} + 2a_AA^{-1}} \), is used to calculate the atomic number \( Z \).
Thus \( Z_{\text{min}} \) is

\[
Z_{\text{min}} = \frac{(939.573 - 938.280 - 0.511003) (\text{MeV}/c^2)c^2 + 93.14 \text{ MeV}/c^2}{2(0.697 \text{ MeV}/c^2)(97)^{-1/3} + 2(93.14 \text{ MeV}/c^2)(97)^{-1}} = 41.88 \approx 42.
\]

From period table, element with atomic number 42 is molybdenum i.e. \(^{97}\)\(^{42}\)Mo.

### 12.1.3 Nuclear Radii

The radius \( r \) of nucleus is normally measured by unit called *Fermi* or *femtometer*, which is \( 10^{-15} \) m. The radius of nucleus is given by equation (12.4).

\[
r = r_0 A^{1/3} \quad (12.4)
\]

where \( r_0 \) is equal to 1.2fm. The volume of a nucleus is proportional to \( r^3 \) and also directly proportional to the mass number \( A \) and is independent of the separate values of \( Z \) and \( N \). Equation (12.2) does not apply to the halo nuclides, whereby they are neutron rich isotope such as lithium \(^9\)Li. The halo nuclides normally have additional increase of radius by few \( 10^\text{th} \) of percent in radius.

The atomic masses can be measured with great precision. The mass is reported in atomic mass unit \( u \). It is chosen with atomic mass of carbon 12 that has exactly \( 12u \). Thus, for example, the atomic mass unit of gold 197 is 196.966573\( u \). Using Einstein’s equation \( E = mc^2 \), it tells us that the mass energy of a mass of \( 1u \) is 931.5MeV, where one \( u \) is approximately equal to 1.660538\( \times 10^{-27} \) kg.

The mass \( M \) of a nucleus is less than the total mass of \( \Sigma m \) of individual protons and neutrons. This shall mean that the mass energy \( Mc^2 \) of nucleus is less than the total mass energy \( \Sigma m \) of individual protons and neutrons. The difference between them is called *binding energy* of the nucleus.

\[
\Delta E_{\text{be}} = \sum (\text{mc}^2) - M c^2 \quad (12.5)
\]

A better measurement is usually done by binding energy per nucleon, which is the ratio of binding energy \( \Delta E_{\text{be}} \) of the nucleus to the \( A \), the number of nucleon in the nucleus. i.e.

\[
\Delta E_{\text{ben}} = \frac{\Delta E_{\text{be}}}{A} \quad (12.6)
\]
Thus, binding energy per nucleon is the average energy required to separate a nucleus into individual nucleons. Figure 12.3 shows that plot of binding energy per nucleon $\Delta E_{\text{be}}$ versus mass number $A$ for a large number of nuclei. The element on the top are tightly bound. This shall mean that there is a need of great amount of energy per nucleon in order to break it apart.

Referring to the graph, the nucleon in a nucleus on the right side of the plot would be more tightly bound if the nucleon were to split into two nuclei that lie near the top of the plot. Such process is called \textit{fission}, which naturally occurs with large nuclei of large atom number such as uranium. Uranium can undergo fission spontaneously. The nucleon in any pair of nuclei on the left side of the graph would be more tightly bound if the pairs were to combine to form a single nucleus that lies nearer to the tip. Such process is called \textit{fusion} occurred naturally in the star like the Sun. Without the Sun, there will not be any life on planet earth.

The energy in nuclei is quantized like the atom. The nuclei can be existence only in discrete quantum states, each with well defined energy. However, unlike the electron, the energy level difference is in terms of million electron-volt. Figure 12.4 shows the energy level of a low mass $^{28}\text{Al}$ nuclide.
Many nuclides have intrinsic nuclear angular momentum, or spin and associated intrinsic nuclear magnetic moment. Nuclear angular moments are roughly of the same magnitude as the angular moments of atomic electrons. Nuclear magnetic moments are much smaller than typical atomic magnetic moments.

The force that controls the motions of atomic electron is electromagnetic force. To bind the nucleus together, there must be a strong attractive nuclear force of a totally different kind, strong enough to overcome the repulsive force between positive charged nuclear protons and to bind both protons and neutrons into the tiny volume. The nuclear force must be of short range because its influence does not extend very far beyond the nuclear surface. The present thought is that nuclear force that binds neutrons and protons together in nucleus is not fundamental force of nature but is a secondary or “spillover” effect of strong force that binds quarks together to form neutrons and protons. This is quite similar to the attractive force between certain neutral molecules. It is spillover effect of Coulomb electric force acting within each molecule to bind together.

Figure 12.4: Energy levels for the nuclide $^{28}$Al deduced from nuclear reaction experiment
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12.2 Radioactive Decay

Many natural occurrence elements have been identified to be radioactive. If a sample contains $N$ radioactive nuclei, then the rate at which the number of nuclei $\frac{dN}{dt}$ will decay is proportional to $N$. i.e.

$$\frac{dN}{dt} = -\lambda N$$  \hspace{1cm} (12.7)

where $\lambda$ is the disintegration constant of decay. If we set $N = N_0$ at time $t = 0$, then the number of radioactive nuclei after time $t$ is the integration of equation (12.7), which yields equation (12.8).

$$N = N_0 \exp(-\lambda t)$$  \hspace{1cm} (12.8)

If we express the rate of decay $R$ as $-\frac{dN}{dt}$ then by differentiating equation (12.8) will yield it, which is

$$R = -\frac{dN}{dt} = \lambda N_0 \exp(-\lambda t)$$  \hspace{1cm} (12.9)

or

$$R = -\frac{dN}{dt} = R_0 \exp(-\lambda t)$$  \hspace{1cm} (12.10)

where $\lambda N_0$ is equal to $R_0$, the rate of decay at time $t = 0$. The rate of decay $R$ is the number of disintegration per time, which is also called activity. One disintegration per second is called one bequerel Bq. A more common unit of activity is the curie Ci, with 1.0Ci equals to $3.7 \times 10^{10}$Bq.

There are two common times that measure for how long the radionuclide is lasts. There are half life $T_{1/2}$ and mean time life time $\tau$. The half time $T_{1/2}$ can be calculated by setting the rate of decay $R$ to be $\frac{R_0}{2}$ and substitute into equation (12.10).

$$\frac{R_0}{2} = R_0 \exp(-\lambda T_{1/2})$$  \hspace{1cm} (12.11)
Taking the natural logarithm of both sides and solving for $T_{1/2}$. It yields equation (12.12).

$$T_{1/2} = \frac{\ln 2}{\lambda}$$  \hspace{1cm} (12.12)

The mean life time is defined as $\tau = \frac{1}{\lambda}$. Substituting mean life time into equation (12.12), it yields equation (12.13).

$$T_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2$$  \hspace{1cm} (12.13)

### 12.2.1 Alpha Decay

When a nucleus undergoes alpha decay, it transforms to different nuclide by emitting an alpha particle. An example of such decay is uranium $^{238}\text{U}$ transforming into thorium $^{234}\text{Th}$ that follows equation (12.14).

$$^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}$$  \hspace{1cm} (12.14)

The disintegration energy $Q$ is the difference between the initial mass energy and the total final mass energy. The disintegration energy $Q$ is found to be $4.25\text{MeV}$. This is the mass energy said to be released due to decay and transferred as kinetic energy of the two final products. The half-life of the decay is $4.5 \times 10^9$ years.

### 12.2.2 Beta Decay

A nucleus that decays spontaneously by emitting an electron or positron is said to be beta decay. Like alpha decay, this spontaneously process has defined disintegration energy and half-life. Examples of such decay process are

$$^{32}_{15}\text{P} \rightarrow ^{32}_{16}\text{S} + e^- + \nu \hspace{1cm} (T_{1/2} = 14.3 \text{ days})$$  \hspace{1cm} (12.15)

and

$$^{64}_{29}\text{Cu} \rightarrow ^{64}_{28}\text{Ni} + e^+ + \nu \hspace{1cm} (T_{1/2} = 12.7 \text{ hrs})$$  \hspace{1cm} (12.16)
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The symbol $\nu$ represents neutrino, which is a neutral particle of very little or no mass. Notice that equation (12.15) is a beta-minus $\beta^-$ decay. It is due to a neutron is transformed into proton, electron, and neutrino following equation

$$n \rightarrow p + e^- + \nu \quad (12.17)$$

For beta-plus $\beta^+$ shown in equation (12.16), a proton is transformed into neutron, positron, and neutrino following equation

$$p \rightarrow n + e^+ + \nu \quad (12.18)$$

Both of beta decay processes provide evidence that neutrons and protons are not truly fundamental particles. These processes show why the atomic mass number $A$ of a nuclide undergoing beta decay does not change. Electron $e^-$ can also be represented as negative beta $\beta^-$. Similarly, Positron $e^+$ can also be represented as positive beta $\beta^0$.

12.2.2.1 Neutrino

The presence of neutrino was first suggested by Wolfgang Pauli in 1930. His neutrino hypothesis is not only permitted an understanding of the energy distribution of electron or positron and beta decay but also solved another early beta decay puzzle involving missing angular momentum.

Energetic neutrino in water has mean free path calculated to not less than several thousand light-year. Neutrino interacts weakly with matter. For this reason, it is difficult to detect its presence. However, it has been detected in laboratory by Frederick Reines and Clyde L. Cowan in 1953.

12.2.2.2 Radioactivity and the Nuclidic Chart

Nuclides with proton-rich will decay into emitting positron and those neutron-rich will emit electron. This is illustrated in the Nuclidic chart shown in Fig. 12.5. The nuclides of low mass like deuterium, tritium, and helium lie at the nearest end of the plot with helium at the high point. The valley stretches away from us. Nuclei at the right side can decay by emitting alpha particle emission and by fission.
Figure 12.5: Nuclidic plot of excess mass energy versus proton number and neutron number

12.2.3 Gama Decay

Gama ray is photon having very high energy. It has its origin from decay of nucleus much like the emission of photon by excited atom. Like an atom, a nucleus itself can be at excited state. When it jumps down to lower energy level state or ground state, it emits a photon which is called gamma ray $\gamma$. As mentioned early the energy level in nucleus is in a few keV to several MeV. Thus, the gamma ray emitted will have this order of energy. Since gamma ray carries no charge, therefore, there is no change in the element as the result of gamma decay.

Let’s look beta decay of boron $^{12}_5B$ to carbon $^{12}_6C$ i.e. $^{12}_5B\rightarrow^{12}_6C+e^-+\nu$. The beta decay can be taken place directly to ground state of carbon $^{12}_6C$ by releasing energy amounted to 13.4MeV. Alternatively, it can have beta decay $\beta^-$ to an excited carbon state $^{12}_6C^*$ amounted to 9.0MeV and subsequently decay to ground state of carbon $^{12}_6C$ by emitting $\gamma$-ray of energy 4.4MeV. Figure 12.6 illustrates the process of decay.
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![Beta decay and gamma ray emission of boron $^{12}$B](image)

**Figure 12.6**: Illustration of beta decay and gamma ray emission of boron $^{12}$B

### 12.2.4 Radioactive Dating

Knowing the half life of a given radionuclide, one can use it to clock the measure time interval. Long half life nuclide can be used to measure the life of rock, which is the time that has lapsed since it was formed. Take for example, radionuclide $^{40}$K decay to $^{40}$Ar, a stable isotope of the noble gas argon. It has half life of $4.5 \times 10^9$ years. The measurement done on the rock from earth, moon, and meteorite has consistently shows that the age of these bodies is $4.5 \times 10^9$ years. Other long life decay such as $^{235}$U to lead $^{207}$Pb can be used to verify the calculation.

For shorter time interval, in the range of historical interest, radioactive carbon dating can be used. The radionuclide carbon $^{14}$ that has half life 5,730 years is produced at a constant rate at the upper atmosphere when atmospheric nitrogen $^{14}$N is bombarded by energetic neutron. The high energetic neutron is produced by cosmic ray when it collides with atom. The radioactive carbon mixes normally with carbon dioxide in about 1 in $10^{13}$ atom of originally $^{12}$C. Carbon dioxide is then used by plant photosynthesis. The food is then consumed by human being, animal etc. Thus, there is fixed fraction of radioactive $^{14}$C present in these organisms due to constant exchange carbon between these organisms, food, and air. When the organism died, the exchange equilibrium stops. i.e. there is no $^{14}$C replenishment from air and food. The fixed fraction of $^{14}$C trapped in the organism undergoes beta decay with half life of 5,730 years into nitrogen $^{14}$C following equation (12.19).

$$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- + \nu$$  \hspace{1cm} (12.19)
By measuring the amount of radiocarbon per gram of organic matter, it is possible to measure the time that has lapsed since the organism died.

12.3 Nuclear Reactions and Transmutation of Elements

When a nucleus undergoes $\alpha$ or $\beta$ decay, the daughter nucleus is different from the parent element. The transformation of one element into another called *transmutation*, also occurs by means of nuclear reactions. A nuclear reaction is said to occur when a given nucleus is struck by another nucleus or by simpler particle such as a $\gamma$ ray or neutron so that an interaction takes place.

For a given nucleus reaction such a proton is accelerated to hit the stationary lithium $^7_3\text{Li}$ as shown in equation (12.18). The difference of initial mass and final mass $\Delta m$ of the reaction can be calculated. If the value is positive, it means the kinetic energy of the product is greater than the reactant. If the mass difference is a negative value, it means the kinetic energy of the product is less than the reactant. Thus, it is necessary to supply energy in order for the reaction to take place.

$$^1_1\text{p} + ^7_3\text{Li} \rightarrow 2^4_2\text{He}$$

(12.20)

For a nuclear reaction such as the one shown in equation (12.21),

$$a + X \rightarrow Y + b$$

(12.21)

The supply energy for the reaction to take place is the threshold energy $KE_{th}$. This threshold energy is the kinetic energy that the proton must acquire in order to cause the reaction to occur. The relation shows that threshold energy and $\Delta mc^2$ energy are given by equation (12.22).

$$KE_{th} = (1 + M_X/M_Y)\Delta mc^2$$

(12.22)

where $M_X$ and $M_Y$ are the mass of moving particle and nucleon at rest respectively and $c$ is the speed of light. $\Delta mc^2$ is also known as Q-value or reaction energy. The reaction that has positive Q-value is said to be exothermic or exoergic. Energy will release in the reaction. If Q-value is a negative value then it is said to be endothermic or endoergic. Energy is needed to make the reaction to happen.
From conservation of energy standpoint, the reaction energy $Q$ is equal to

$$Q = KE_a + KE_\gamma - KE_a - KE_\chi$$  \hspace{1cm} (12.23)

This $Q$-value should be equal to the threshold kinetic energy $KE_{th}$ required for an endoergic nuclear reaction to take place. However, it violates conservation of momentum since particle $X$ has momentum and it cannot produce a $b$ particle without momentum. Thus, the kinetic energy of a particle necessary to initiate endoergic nuclear reaction has to be more than $Q$-value, which is shown in equation (12.23).

In 1930, Enrico Fermi found that neutron is the most effective projectile for causing nuclear reactions in particular to produce new elements. This is due to the fact that neutron has no net charge and would not repel by positively charged nuclide. Figure 12.7 shows the new element neptunium and plutonium are being produced from bombardment of neutron to $^{238}\text{U}$.

The new elements such as neptunium and plutonium are called transuranium elements. The latest transuranium element is ununoctium (the name is not finalized yet), which has atomic number 118 and atomic weight 294.

(a) Neutron captured by $^{238}\text{U}$ to form $^{239}\text{U}$

(b) Uranium $^{239}\text{U}$ decays by $\beta$ decay to neptunium $^{239}\text{Np}$

(c) Neptunium $^{239}\text{Np}$ decays by $\beta$ decay to plutonium $^{239}\text{Pu}$

Figure 12.7: Neptunium and plutonium are produced from bombardment of neutron to $^{238}\text{U}$

12.3.1 Cross Section of Reaction

Some reactions have a higher probability of occurring than others. The reaction probability is specified by a quantity called cross section. Supposing a projectile particle strikes a stationary target of cross sectional area $A$ and thickness $t$ that contains of $n$ nuclei per unit volume as shown in Fig. 12.8.
Figure 12.8: Projectile particles fall on a target area $A$ of thickness $t$ made up of $n$ nuclei per unit volume

If the cross sectional area of a nucleus is $\sigma$ then the total cross sectional areas $A'$ of all nuclei for the volume as shown in Fig. 12.8 will be

$$A' = nAt\sigma \quad (12.24)$$

Since $A' \ll A$, this shall mean most of the incident projectile particles will pass through the target without colliding. If $R_0$ is the rate at which the projectile particles strike the target then the rate at which collision occur $R$ is

$$R = R_0 \frac{A'}{A} = R_0 \frac{nAt\sigma}{A} \quad (12.25)$$

### 12.4 The Basic Process of Nuclear Fission

In 1932, English physicist James Chadwick discovered neutron. A few years later, Enrico Fermi in Rome found that when various elements are bombarded by neutrons, new radioactive elements are produced. Fermi had predicted that the neutron being uncharged would be a useful nuclear projectile. Unlike alpha particle or proton, they experience repulsive force when they are near the nuclear surface. A thermal equilibrium neutron of kinetic energy about 0.04eV is useful projectile in nuclear studies.
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In 1930s physicist Lise Meitner and Chemists Otto Hahn and Fritz Wilhelm Strassmann working on bombarded solution of uranium salt with thermal neutrons found a number of radionuclides were present. This is a process of fission whereby uranium absorbed thermal neutron and spitted into roughly equal parts with energy released in which it was explained by Meitner and her nephew Otto Robert Frisch a few weeks later.

An average up to 200MeV of energy can be released from uranium fission. As compared with chemical reaction, an average of 1.0eV is released per molecule. Uranium $^{235}\text{U}$ absorbed thermal neutron becomes highly excited nucleus compound $^{236}\text{U}$. This nucleus undergoes fission splitting into two fragments. The two fragments rapidly emit two neutrons leaving xenon $^{140}\text{Xe}$ and strontium $^{94}\text{Sr}$ fission fragments. The overall fission equation is shown in equation (10.26).

$$^{235}\text{U} + {\text{n}} \rightarrow ^{236}\text{U} \rightarrow ^{140}\text{Xe} + ^{94}\text{Sr} + 2(\text{n})$$  \hspace{1cm} (12.26)

Two prompt neutrons and one delay neutron released from this fission can cause other fissions to release more neutrons and energy. Such process is called chain reaction as illustrated in Fig. 12.9.

Figure 12.9: Schematic showing chain fission reaction of uranium $^{235}\text{U}$
If the process is carried out such that it controls the number of neutron used for successive fission then the heat due to kinetic energy can be extracted and made to do work such as the nuclear fuel power plant. Controlling the number of neutron can be done using a moderator such as lead to reduce the energy of neutron by collision. Illustration of the use of moderator is shown in Fig. 12.10.

![Moderator (Lead) and Neutron Diagram](image)

**Figure 12.10:** Illustration the use of moderator for controlling the number of neutron

Figure 12.11 shows the basic components of a fission power plant. In 1942, Enrico Fermi and his colleagues at University of Chicago had successfully accomplished first self-sustaining controlled nuclear chain reaction.

![Fission Power Plant Diagram](image)

**Figure 12.11:** The basic components of a fission power plant
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Based on reaction shown in equation (12.26), fragment $^{140}\text{Xe}$ and $^{94}\text{Sr}$ are both high unstable. They will undergo beta decay with the conversion of a neutron to proton and emission of an electron and a neutrino. The decay processes are as follow.

$$^{94}\text{Sr} \rightarrow ^{94}\text{Y} + e^{-} + \nu \rightarrow ^{94}\text{Zr} + e^{-} + \nu \quad (12.27)$$

and

$$^{140}\text{Xe} \rightarrow ^{140}\text{Cs} + e^{-} + \nu \rightarrow ^{140}\text{Ba} + e^{-} + \nu \rightarrow ^{140}\text{La} + e^{-} + \nu \rightarrow ^{140}\text{Ce} + e^{-} + \nu \quad (12.28)$$

From equation (12.26), (12.27), and (12.28), the overall fission equation of uranium $^{235}\text{U}$ can be written as

$$^{235}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}\text{U} \rightarrow ^{140}\text{Ce} + ^{94}\text{Zr} + 2(^{1}_{0}\text{n}) + 2e^{-} \quad (12.29)$$

Figure 12.12 shows the distribution by mass number of fragments that are found with many fission events of $^{235}\text{U}$.

![Graph showing the distribution by mass number of fragments](image)

**Figure 12.12:** The distribution by mass number of fragments that are found when many fission events of $^{235}\text{U}$
Example 12.2
Find the disintegration energy of the fission reaction shown in the following equation; \( ^{235}_{92}U \rightarrow ^{140}_{54}Ce + ^{94}_{40}Zr + ^{1}_{0}n + 2e^- + \nu \). Given that the atomic mass unit of \( ^{235}_{92}U , ^{140}_{54}Ce , ^{94}_{40}Zr , ^{1}_{0}n \), and \(^{0}_{-1}e\) are 235.0439u, 139.9054u, 93.9063u, 1.00867u, and 0.000548579u respectively.

Solution
The delta mass is \( \Delta m = 235.0439u - 139.9054u - 93.9063u - 1.00867u - 2 \times 0.000548579u = 0.2224328u \).

The disintegration energy is equal to \( 0.2224328u \times 931.5\text{MeV}/u = 207.2\text{MeV} \).

12.5 Thermonuclear Fusion

Figure 12.3 shows that energy can be released if two light nuclei combine to form a single nucleus. This is a process of fusion. An example of fusion process is shown in equation (12.30).

\[ ^{1}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{1}\text{He} + ^{0}_{0}n \]  \hspace{1cm} (12.30)

\(^{1}_{1}H\) is the naturally occurred isotope of hydrogen called deuterium.

The process is hindered by two positively charged particles from getting close enough to be within range of their attractive nuclear forces and then fusing. The height of the coulomb barrier depends on the charges and radii of the two interacting nuclei. The Coulomb potential for two deuterium nuclei separated by a distance \( 10^{-15} \text{m} \), the approximated distance that nuclear fusion is \( \frac{q^2}{4\pi\varepsilon_0 r} \). This energy is equal to 400keV.

For fusion to be self-sustaining, its energy must be released in the vicinity of other deuterium nuclei so that they can subsequently interact. The temperature of deuterium gas in which the particles would have an average kinetic energy of 400keV can be determined from kinetic energy of gas equation, which is \( \overline{KE} = \frac{3}{2}kT \). The temperature is found to be approximately equal to \( 3.0 \times 10^9 \text{K} \). Such high temperature gas of positive and negative charged particles is called plasma.
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Thus, in order to generate useful amount of energy, a nuclear fusion must occur in bulk matter. The best way for bringing it to happen is to raise the temperature of the material until the particles have enough energy due thermal motion alone to penetrate the Coulomb barrier, which requires energy 400keV. This process is called \textit{thermonuclear fusion}. One of the most likely methods to accomplish self-sustaining fusion reaction on earth is to compress a high temperature plasma using magnetic field.

The kinetic energy $KE$ of interacting particles via the relation $KE = kT$. The Sun has center temperature equal to $1.5 \times 10^7 K$. Thus, the kinetic energy of the interacting particle at the center of Sun is 1.29keV, which is much lower than 400keV. However, 1.29keV is the most probable kinetic energy. There is a long tail of particle of much higher energy that is able to penetrate Coulomb barrier. The particle is not necessary needed to overcome the peak of the barrier before fusion occurred. Barrier tunnel can occur at energy much lower than the peak. Figure 12.13 shows the distribution curve of kinetic energy $n(KE)$ at the center of Sun and the probability $p(KE)$ of barrier penetration leading to fusion.

![Figure 12.13: The kinetic energy distribution at the center of the Sun and the probability of nuclear fusion](image)

12.5.1 Thermonuclear Fusion in the Sun and Other Stars

The Sun radiates energy at the rate of $3.9 \times 10^{20}$W and has been going for several billion years. The fusion mechanism in the Sun is a multistep process in which hydrogen is burned into helium, hydrogen being the fuel and helium the ash.
The mechanism is a proton-proton cycle, which is shown in Fig. 12.14, when it begins two protons collision to form deuteron with simultaneous creation of positron and neutrino. The positron quickly encounters a free electron in the Sun to form two gamma ray photons. This is reaction is extremely rare. It occurs once in $10^{26}$ proton-proton collisions. Despite this low rate of occurrence, there are so many protons in huge and dense volume of Sun’s core that deuterium is produced in this way at the rate of $10^{12}$kg/s.

Once the deuteron is formed, it quickly collides with another proton and form helium $^3$He nucleus. Two $^3$He may eventually form an alpha particle $^4$He and two protons. The overall proton-proton cycle amounts to the combination of four protons and two electrons to form an alpha particle. The equation is shown below.

$$4^1\text{H} + 4e^- \rightarrow 2^4\text{He} + 2e^- + 2\nu + 6\gamma$$  \hspace{2cm} (12.31)

The amount of energy released for the fusion mechanism shown in equation (12.31) is 26.7MeV. About 0.5eV of energy is carried by two neutrinos, the rest of 26.2MeV is deposited as thermal energy in the core of the Sun.

![Figure 12.14: The proton-proton mechanism that account for energy produced by the Sun](image)

Hydrogen burning in the Sun has been going on for $5.0 \times 10^9$ years. The calculation shows that it has another $5.0 \times 10^9$ years to live. In $5.0 \times 10^9$ years from now, the core of Sun would be largely helium. It will begin to cool and collapse due to its own gravity. This will raise the core temperature and cause the outer envelope to expand, turning the Sun into red giant.

If the core temperature can be raised to about $10^8$K, this time it causes another fusion mechanism by burning helium in the triple alpha process and turning into carbon. However, this fusion mechanism will stop when element
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with mass number at the peak of curve shown in Fig. 12.3 is formed. This mass number is 68 and is belong to nickel \(^{68}\text{Ni}\). However, nickel 68 is unstable and quickly disintegrated in iron \(^{64}\text{Fe}\).

Elements with mass number beyond peak of the curve are thought to be formed by neutron capture during cataclysmic stellar explosion that it is called supernovas. In such an event the outer shell of the star is blown outward into space.

Example 12.3
The power released by the Sun is \(3.90\times10^{26}\text{W}\). Calculate the quantity of hydrogen consumed per second to release this power.

Solution
From equation (12.31), four hydrogen atoms released 26.7MeV, which is \(4.27734\times10^{-12}\text{J}\).
\[3.90\times10^{26}\text{J} \text{ required } 3.90\times10^{26}\text{J}/4.27734\times10^{-12}\times4 = 3.64712\times10^{38} \text{ hydrogen atoms. This number of atoms equal to } 3.5712\times10^{38}/6.022\times10^{23} = 5.93\times10^{14} \text{ moles.} \]

One hydrogen atom has \(1.007825u\), which \(1.007825u\times1.660538\times10^{-27}\text{kg}/u = 1.673531\times10^{-27}\text{kg}\). One mole of hydrogen weighs \(1.673531\times10^{-27}\text{kgx6.022x10}^{23} = 1.0078\times10^{-3}\text{kg}\).

The amount of hydrogen used per second to release \(3.90\times10^{26}\text{W}\) is \(5.93\times10^{14}\times1.0078\times10^{-3}\text{kg} = 5.97\times10^{11}\text{kg}\).

12.5.2 Terrestrial Thermonuclear Fusion

Proton-proton mechanism happened in the Sun is not suitable for the earth bound fusion reactor because it is hopeless slow. This process is successful in the Sun is because there is enormous density of protons in the core of Sun. The most attractive reactions for terrestrial use appear to be two deuteron-deuteron reactions as shown by equation (12.32) and (12.33).

\[
\begin{align*}
\text{1}_1^2\text{H} + \text{1}_1^2\text{H} & \rightarrow \text{2}_2^3\text{He} + \text{n} & \text{(12.32)} \\
\text{1}_1^2\text{H} + \text{1}_1^3\text{H} & \rightarrow \text{2}_1^3\text{H} + \text{1}_1^2\text{H} & \text{(12.33)}
\end{align*}
\]

and the deuteron-triton reaction shown in equation (12.34).
Deuterium, the source of deuteron for the reaction, is an isotope abundance of only 1 part in 6,700 but it is available unlimited quantities as a component of sea water.

There are three requirements for a successful thermonuclear reactor.

1. A high particle density \( n \). The density of interacting particles must be high enough to ensure deuteron-deuteron collision is high enough.

2. A high plasma temperature \( T \). The plasma must be hot. Otherwise, the colliding deuterium will not be energetic enough to penetrate Coulomb barrier that tends to keep them apart. A plasma ion temperature of \( 4.0 \times 10^8 \text{K} \) has been achieved in laboratory, which is 30 times higher than the Sun’s core temperature.

3. A long confinement time \( \tau \). A major problem is containing the hot plasma long enough to maintain it at a density and a temperature sufficiently high to ensure the fusion of enough fuel. Since the temperature is so high, no solid container can confine the plasma. Thus, a clever confinement technique is required such as magnetic confinement and inertial confinement.

For deuteron-triton reaction to occur, it is necessary to ensure the product of particle density and confinement time be greater than \( 10^{20} \text{s/m}^3 \). This condition is called Lawson’s criterion.

**12.5.2.1 Magnetic Confinement**

Magnetic field is used to confine hot plasma in an evacuated doughnut shaped chamber as shown in Fig. 12.1 called *Tokamak*. The magnetic force acting on the hot charged plasma keeps plasma from touching the wall of the chamber. Tokamak was invented in the 1950s by Soviet physicists Igor Tamm and Andrei Sakharov, inspired by an original idea of Oleg Lavrentiev.
Plasma is heated by inducing current to flow in it and by bombarding the plasma with an externally accelerated beam of particles. The approach is to break even when Lawson criterion is met or exceeded this value. The ultimate objective is to ignite the fusion reaction. In October 2012, a report stated that successful fusion was done with HT-7 Tokamak reactor in Hefei, China.

12.5.2.2 Inertial Confinement

This approach of confinement is heating the fusion fuel so that a thermonuclear reaction can occur involving “zapping” a solid deuterium–tritium fuel pellet from all sides with intense laser beam evaporating some materials from the surface of pellet. The boiled off material causes an inward moving shock wave that compresses the core of the pellet increasing both its particle density and temperature. The process is called inertial confinement. The reason being the fuel is confined to the pellet and the particles do not escape from the heated pellet during the very short zapping interval because of their inertia. Figure 12.16 shows the target chamber of the NOVA Laser Facility at Lawrence Livermore Laboratory, a facility has been replaced by an even larger one at the National Ignition Facility. In October 2013, it showed a breakthrough of the inertial confinement method at National Ignition Facility in the USA.
Figure 12.16: (a) The NOVA laser showing some of the arms through which the laser power is focused on the fuel pellet at the center. (b) View of the artificial minister created by inertial confinement fusion in the NOVA.

Figure 12.17 shows the approach to breakeven and ignition in controlled fusion reactor. It is shown as the plot of Lawson number against temperature. The year indicated the ion temperature and Lawson’s number achieved.

Example 12.4

Suppose a fuel pellet in laser fusion device contains equal numbers of deuterium and tritium atoms. The density \( d = 200 \text{kg/m}^3 \) of the pellet is increased by a factor of 10^3 by the action of the laser pulse. How many particles per unit volume for both deuterium and tritium does the pellet contain in compressed state? The molar mass \( M_d \) of deuterium atom is 2.0 \times 10^3 \text{kg/mol} and molar mass \( M_t \) of tritium atom is 3.0 \times 10^3 \text{kg/mol}. 

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Solution
Let \( n \) be the total number of particles per unit volume in the compressed pellet. Then the number of deuterium atom and tritium is \( n/2 \) respectively.

In the laser fusion device, the density of the compressed pellet is \( d^* \) and it is equal to 
\[
d^* = \frac{n}{2} m_d + \frac{n}{2} m_t,
\]
where \( m_d \) and \( m_t \) are mass deuterium and tritium atoms.

The mass of deuterium \( m_d \) and tritium \( m_t \) is also equal to 
\[
m_d = \frac{M_d}{N_A} \quad \text{and} \quad m_t = \frac{M_t}{N_A}.
\]

The pellet density is increased by \( 10^3d^* \) thus, 
\[
d^* = \frac{n}{2} m_d + \frac{n}{2} m_t = 1.000d.\]

Thus, 
\[
2.000d = n \frac{M_d}{N_A} + n \frac{M_t}{N_A}.
\]

The total number of particles per unit volume in the compressed pellet \( n \) is 
\[
n = \frac{2.000dN_A}{M_d + M_t} = \frac{2.000 \times 200 \times 6.02 \times 10^{23}}{2.0 \times 10^3 + 3.0 \times 10^3} = 4.816 \times 10^{31} \text{m}^{-3}.
\]

12.6 Applications of Nuclear Physics

There are many applications of nuclear physics. We have discussed a few in the previous sections like carbon dating for archeologically study, conversion of fission energy into electrical energy, and transmutation of elements. Let’s discuss briefly a few more applications and further elaborating synthesis of new elements.

12.6.1 Neutron Activation Analysis

Nearly every radioactive isotope emits gamma ray. Thus, many chemical elements can be identified by its gamma ray spectrum. From the rate of gamma ray emission, one can deduce exactly what is the element in the material. This technique is called neutron activation analysis.

Neutron activation analysis is a non destructive technique, which is widely used to examine oil painting. Thermal neutron beam from a nuclear reactor is spread broadly and evenly over the painting. Several elements within the painting become radioactive. x-ray film sensitive to beta emission from radioactive nuclei are subsequently placed next to the painting for varying length of time. This method called autoradiograph has been used by art
historian to identify modern repairs of the painting as well as to see the under
drawing of the original figures in painting.

Neutron activation analysis is also useful to search for particular elements
indicative of crime. The examination of gunshot by measuring trace amounts of
barium and antimony from the gunpowder have been proven to be 100 to 1,000
times more sensitive than looking for the reside.

Scientist is also able to detect toxic element in hair by neutron activation
analysis. Human hair grows about 10cm/year. Small amount of arsenic and
mercury may be detected and time of poisoning may be determined.

12.6.2 Medicine

One of the most important applications of nuclear physics has been in medicine
are for diagnostic and therapeutic purposes. The use of x-ray for producing
image for medical diagnosis is already well known but it has limitation. It
cannot show the image of soft tissue due low absorptive coefficient of x-ray by
the soft tissue.

Radioactive isotope can be introduced into body in chemical form that has
an affinity for certain organ such as bone or thyroid gland. A sensitive detector
such as gamma ray camera can observe the radiation from the isotope, which is
concentrated in the organ, can produce an image showing the activity
distribution of the organ of patient. Figure 12.18 shows an image of brain taken
after the patient was injected with the radioactive isotope technetium $^{99m}$Tc with
half life of 6.0hrs. The image has clearly shown an area of brain that has high
concentration of activity. White area shows concentration of blood possibly a
tumor.

![Image](image_url)

**Figure 12.18:** Scintillation camera image of brain after intravenous injection of 20mCi of
$^{99m}$Tc.
Another technique which can reveal a wealth of information is positron emission tomography PET. The patient is injected with glucose labeled with positron emitting isotope that readily can be absorbed by the body. Examples of isotopes are oxygen $^{15}$O with half life 2 minutes, nitrogen $^{12}$N with half life 10 minutes, carbon $^{11}$C with half life 20 minutes, and fluorine $^{19}$F with half life 110 minutes.

The isotopes are produced using cyclotron at the diagnostic due to short half life. When the positron emitter decays, the positron quickly annihilates with electron and produces two 511keV gamma rays that travel in opposite directions. By surrounding the patient with a ring of detector, it is possible to determine exactly where the decay occurred and a large number of such events, the physician can produce an image that reconstructs the distribution of the radioisotope in the patient.

Radiotherapy takes advantage of the effect of radiation in destroying unwanted tissue in the body such as a cancerous growth or an overactive thyroid gland. The effect of the passage of radiation through matter is often to ionize atom. The ionized atom can then participate in chemical reaction that lead to its incorporation into molecule and subsequently alteration of its biological function, possibly destruction of a cell or modification of its genetic material.

Medical research often uses radioactive tracers as an in vitro tool. Some of the earliest usages were to map out biochemical pathways. Radioactive tracers can be used to determine the rate of metabolic processes, predominant pathway for biosynthesis and metabolism reactions, and spatial localization information.

Tracers can also be used for sample too small for chemical testing. Radioimmunological assay can determine the amount of an antigen present even in tiny amount. A minute measured amount of radio labeled antigen is added to the sample along with a measured small amount of antibody, small enough that it is all fully bound with antigen. The antigen will bind to the antibody independent of irrespective it is labeled. When centrifuged, the antibody-antigen complex can be physically separated from the unbound antigen and the activity of each fraction can be determined. The ratio of labeled-to-unlabeled antigen bound to the antibody will reflect the same ratio as found in solution. The amount of labeled antigen added is known. Thus, the amount of antigen in the original sample can simply be calculated from the ratio. There are radioimmunological tests for literally hundreds of drugs or proteins found in the blood, urine, and other bodily fluids.
12.6.3 Small Power System from Alpha Decay

Alpha particle emission radioactive sources such as americium $^{241}$Am or plutonium $^{238}$Pu have been used as power sources in heart pacemaker and smoke detector. Alpha particle of americium $^{241}$Am is used as the source of current in the smoke detector. The scattering of the alpha particle by the smoke reduces the current flowing to sensitive solid state device, which results in an alarm.

Spacecraft has been powered by radioisotope generator RTG since early 1960’s. These devices used the heat generated from alpha decay of plutonium $^{238}$Pu to produce electricity in thermocouple circuit. Current RTG can supply almost 300W and usually more than one unit is installed in spacecraft.

Alpha particle scattering is used for material analysis. In Rutherford back scattering technique, the analysis uses the reduction in energy of alpha particle which is scattered through an angle $180^\circ$. By allowing the target nucleus to recoil, one can find the loss of kinetic energy $\Delta KE$ of an alpha particle that scattered through $180^\circ$, which follows equation (12.35).

$$\Delta KE = KE \left( \frac{4m/M}{(1 + m/M)^2} \right) \quad (12.35)$$

where $m$ is the mass of alpha particle and $M$ is the mass of the target nucleus. For heavy nucleus such that $m/M = 0.02$, the loss of kinetic energy is in of order 0.5MeV, which can be measured. Figure 12.19 shows a sample spectrum of alpha particles back-scattered from a thin foil containing copper, silver, and gold. Note that $Z^2$ dependence of the scattering probability is characterized Rutherford scattering. Depending on the isotope of element, this technique may not resolve them. Back scattering is used to analyze the soil of Moon when Surveyor spacecraft landed on it and the soil of Mars when Viking Lander landed on it.
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Figure 12.19: Back scattering spectrum of 2.5MeV alpha particle from a thin of copper, silver, and gold

12.6.4 Synthesis of New Elements

Transuranic element is not found naturally because of their short half life. However, with the use of reactor and especially accelerator, scientist has been able to produce 24 of these elements that have atomic number beyond 92 up to 118. More than 200 new isotopes heavier than uranium have been discovered. Examples are neptunium and plutonium, which were discovered in Berkeley in 1940.

Certain isotopes including californium $^{252}$Cf have been produced in sufficient quantities in high flux reactor. One of nuclear reaction is to synthesize an isotope of californium, which has the nuclear reaction $^{242}$Cm$^+{^4}$He$\rightarrow^{245}$Cf$+{^1}$n.

All transuranic element nuclei are unstable, with half-lives ranging from approximately $10^9$s to $10^{17}$s. The longest-lived nuclei are those with lower values of atomic number Z. Examples are plutonium $^{238}$Pu with half life 96.4 years, americium $^{241}$Am with half life 433 years, and curium $^{242}$Cm with half life 162.5 days. As Z increases, the life times become shorter with the life times of the heaviest elements being tiny fractions of a second. For elements with atomic number $Z \geq 107$, there are few nuclei whose life-times is too short.
that can lend themselves to chemical studies. Examples are bohrium $^{262}$Bh with half life 102ms, hassium $^{265}$Hs with half life 1.8ms, and meitnerium $^{266}$Mt with half life 3.4ms.

Transuranic reactions can be divided into four classes, which are neutron-induced reaction $(Z=93, 95, 99, 100)$, light-charged particle-induced reaction $(Z=94, 96-98, 101)$, “hot fusion” reaction $(Z=102-106, 114, 116)$, and “cold fusion” reaction $(Z=107-112)$. In neutron-induced nuclear reaction, the capturing of a neutron does not create a new element but the subsequent beta decay produce new element. Example is the synthesis of neptunium 239 with the nuclear reaction $\gamma + ^{238}\text{U} \rightarrow ^{239}\text{U} + \gamma$ and subsequently beta decay with nuclear reaction $^1\text{n} + ^{239}\text{U} \rightarrow ^{239}\text{Np} + ^0\beta$. Light-charged particle reaction with exotic actinide target nuclei allows one to increase the atomic number of the product by one or two from the target nucleus. To make the heaviest elements, one needs to add several protons to the target nucleus by a reaction with a heavy ion. Such “hot fusion” reaction with actinide target nuclei leads to highly excited intermediate species which decay mostly by fission but occasionally by emitting neutrons, thus producing new nuclei. However, as the atomic number of the product nuclei increases, so does the probability of fission leading to very poor survival probabilities for the putative new species. The Russian nuclear physicist Yuri Oganessian pointed out a way to solve this problem was to fuse heavier projectile nuclei with nuclei in the lead-bismuth region. Owing to the special stability of the lead-bismuth nuclei, the resulting fused species would be formed “cold” with some reasonable probability, decay by only emitting a single neutron.

12.7 Biological Effect of Radiation

It is well known that excessive exposure to radiation including sunlight, x-ray and all nuclear radiations can destroy tissues. In the mild case, it results burn. Greater exposure can cause massive destruction of tissue cells, alteration of genetic material, and destruction of the components in bone narrow.

12.7.1 Calculation of Radiation Dosage

Radiation dosimetry is the quantity description of the effect of radiation on the living tissue. The absorbed dose of radiation is defined as the energy delivered to the tissue per unit mass. The unit of absorbed dose is joule per kilogram,
which is called *gray* Gy. Another unit that is more commonly used is the *rad*, which defined as 0.01J/kg.

Absorbed dose itself is not a sufficient measure of biological effect because equal energies of different kinds of radiation cause different extent of biological effect. This variation is described by a numerical factor called the relative biological effectiveness RBE, which is also the quality factor QF of each specific radiation. Figure 12.20 shows the relative biological effective RBE for several types of radiation. All these values depend somewhat on the kind of tissue in which is absorbed and on the energy of the radiation.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>RBE (Sv/Gy or rem/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-ray and γ ray</td>
<td>1</td>
</tr>
<tr>
<td>Electron</td>
<td>1.0-1.5</td>
</tr>
<tr>
<td>Slow neutron</td>
<td>3-5</td>
</tr>
<tr>
<td>Proton</td>
<td>10</td>
</tr>
<tr>
<td>α particle</td>
<td>20</td>
</tr>
<tr>
<td>Heavy ion</td>
<td>20</td>
</tr>
</tbody>
</table>

*Figure 12.20:* Relative biological effective RBE for several types of radiation

The biological effect is described by the product of the absorbed dose Gy and RBE of the radiation. This quantity is called the *biological equivalent dose* or simple equivalent dose. The SI unit of equivalent unit for human is Sievert Sv. Thus,

\[
\text{Equivalent dose Sv} = \text{RBE} \times \text{absorbed dose Gy} \tag{12.36}
\]

A more common unit corresponding to the rad is rem, which röntgen equivalent unit for man. Thus,

\[
\text{Equivalent dose rem} = \text{RBE} \times \text{absorbed dose rad} \tag{12.37}
\]

Note that 1 rem = 0.01Sv.

**12.7.2 Radiation Hazard**

An ordinary chest x-ray examination delivers 0.20 to 0.40mSv to about 5.0kg of tissue. Radiation exposure from cosmic ray and natural radioactivity in soil, building materials, and etc. is in the order 1.0mSv per year at sea level and twice the amount at an elevation of 1,500m. A whole body dose up to about
0.2Sv causes no immediate detectable effect. A short term whole body dose of 5.0Sv or more usually causes death with a few days or weeks. A localized dose of 100Sv causes complete destruction of the exposed tissue.

Long term hazard of radiation exposure casing various cancers and genetic defect have been widely publicized and the question of whether there is any safe level of radiation exposure is a hot topic of discussion. Based on US regulation the yearly exposure to radiation except the natural resource is 2 to 5mSv per year. However, based on the study in US natural resource contribute 82% of radiation received by the population if USA. Radon gas contributes 52%, internal 11%, terrestrial 8%, and cosmic ray 8%. From human activity, it contributes 18% mainly from occupational 0.3%, nuclear fuel cycle 0.1%, consumer product 3%, nuclear medicine 4%, and medical x-ray 11%.

**Example 12.5**
During a diagnostic x-ray examination a 1.2kg portion of a broken leg receives an equivalent dose of 0.40Sv.

(a). What is the equivalent dose in mrem?
(b). Determine the absorbed dose in mrad and mGy?
(c). Find the number of photons are absorbed if the x-ray has energy 50keV.

**Solution**
The equivalent dos in mrem is 0.04mSv/0.01Sv/rem = 40mrem.

The absorbed dose in mrad and mGr 40mrem/1rem/rad = 40mrad and 0.40mSv/1Sv/Gy = 4.0x10^{-31}J/kg.

The total energy absorbed by the leg is 1.2kgx4.0x10^{-31}J/kg = 4.8x10^{-4}J or 3.0x10^{15}eV. The energy of a photon of x-ray is 5.0x10^{4}eV. Thus, the number photon absorbed is 3.0x10^{15}eV/5.0x10^{4}eV = 6.0x10^{10} photons

**Tutorials**

12.1. Assuming the nucleus is a round sphere, prove that the density $\rho$ of nucleus is $\rho = \frac{m}{\frac{4}{3}\pi r_o^3}$, where $r_o$ is equal to 1.2fm and m is mass of proton
which about the same as mass of neutron.
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12.2. Find the neutral atomic mass of $^{62}_{28}$Ni using the semi-empirical mass formula.

12.3. What should the element stable in isobars 80?

12.4. A 5.3MeV alpha particle happens by chance to head directly toward the nucleus of gold atom. How close does the alpha particle get to the center of nucleus before it comes momentarily to rest and reverse its motion?

12.5. Show that the energy of one mass unit $u$ is equal to 931.5MeV.

12.6. Tin $^{120}$Sn consists of 50 protons and 70 neutrons. Calculate the binding energy and binding energy per nucleon. Given that the atomic mass unit of $^{120}$Sn, proton, and neutron are respectively equal to 119.902199u, 1.007925u, and 1.008665u respectively.

12.7. Find the energy release if two deuterium $^2_1$H nuclei can fuse together to form helium $^4_2$He nucleus. The binding energy per nucleon of $^2_1$H and $^4_2$He is 1.1MeV and 7.0MeV respectively.

12.8. The disintegration constant of $^{128}$I is -0.0275min$^{-1}$. What are the half-life and mean life time of this nucleon?

12.9. For an alpha decay of uranium 238 i.e. $^{238}$U$\rightarrow^{234}$Th+$^4$He. Show that the disintegration energy is 4.25MeV.

12.10. Determine whether $^{210}_{84}$Po can decay by emission of an $\alpha$-particle and if so find the kinetic energy released in the process. Given that the atomic mass unit of polonium 210 is 209.98285u, lead 206 is 205.97440u, and helium 4 is 4.00260u.

12.11. Nitrogen 12 decays to an excited state of carbon 12, which subsequently decays to the ground state with the emission of 4.43MeV gamma ray. What is the maximum kinetic energy of the emitted beta particle? And a diagram to illustrate the process of decay.

12.12. Three rock samples have ratios of number of $^{238}$U and $^{206}$Pb atoms of 0.5, 1.0, and 2.0 respectively. Calculate the ages of these rock samples and comment the results. The half life of $^{238}$U is 4.471x10$^9$ years.
12.13. Mass spectrometric analysis of potassium and argon atoms in a Moon rock sample shows that the ratio of the number of stable \(^{40}\text{Ar}\) atom present to the number of radioactive \(^{40}\text{K}\) atom is 10.3. Assuming that all the argon atoms were produced by the decay of potassium with half life of \(1.25 \times 10^9\) years. Find the age of the rock.

12.14. The ratio of \(^{235}\text{U}\) and \(^{238}\text{U}\) in natural uranium deposit is today is 0.0072. What is this ratio \(2.0 \times 10^9\) years ago? The half lives of two isotopes are \(7.04 \times 10^8\) years and \(44.7 \times 10^8\) years.

12.15. Carbon 14 \(^{14}\text{C}\) has half-life of 5,730 ± 40 years. Naturally, 1 part of \(^{14}\text{C}\) per trillion of carbon is found in the atmosphere. 0.34 part \(^{14}\text{C}\) per trillion of carbon is found in an archaeological sample. Calculate the estimated age of the sample.

12.16. A 5.00g charcoal sample from an ancient fire pit has \(^{14}\text{C}\) activity of 63.0 disintegrations/min. A living tree has a \(^{14}\text{C}\) activity of 15.3 disintegration/min per 1.00g. The half life of \(^{14}\text{C}\) is 5,730 years. Calculate the age of charcoal sample.

12.17. The graph below shows that measurement of decay rate of \(^{128}\text{I}\) used to treat thyroid gland enlargement. Calculate the half life \(^{128}\text{I}\) and initial rate of decay for \(^{128}\text{I}\).
12.18. A sample of 1.0g of a radioactive isotope of atomic weight 208 decays via β emission and 75 counts are recorded in a 24 hours period. If the detector efficiency is 10%, estimate the mean life of the isotope.

12.19. Natural lanthanum has an atomic weight of 138.91 and contains 0.09% of the isotope $^{138}_{57}$La. This has two decay modes: $^{138}_{57}$La $\rightarrow ^{138}_{58}$Ce $+$ e$^{-}$ $+$ ν (β-decay), and $^{138}_{57}$La $+$ e$^{-}$ $\rightarrow ^{138}_{56}$Ba$^{\ast}$ $+$ ν (electron capture), followed by the electromagnetic decay of the excited state $^{138}_{56}$Ba$^{\ast}$ $\rightarrow ^{138}_{56}$Ba $+$ γ (radioactive decay). There are $7.8 \times 10^2$ β$^{-}$ particles emitted per second per kilogram of natural lanthanum and there are 50 photons emitted per 100β$^{-}$ particles. Estimate the mean life time of $^{138}_{57}$La.

12.20. Suppose one wish to authenticate animal skin remains from one of the earliest known collections of animals from Shulgi, a Sumerian ruler of a territory now in Iraq, dating back to 2,094 BC. One takes a small sample of the skin and chemically analyzes it for carbon. From a 10g sample of carbon, what is the rate of decay that one would expect to measure if the sample is indeed authentic?

12.21. If we take the mass of Sun to be $1.99 \times 10^{30}$kg, calculate the amount energy it has taking the dominant energy release reaction follows equation $4(^{1}\text{H})$ $\rightarrow ^{2}\text{He} + 2(^{0}\text{e}) + 2\nu + \gamma$. Given that 1 atomic mass unit is $1.66053892 \times 10^{-27}$kg, the atomic mass unit $u$ of a hydrogen atom is $1.007825u$, the atomic mass unit $u$ of a positron is $0.000549u$, and the atomic mass unit of helium is $4.002603u$. 

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