7 NUCLEAR PHYSICS

The structure of atoms is now well understood: Quantum physics governs all, the force law is Coulomb's law; there is a massive force center - the nucleus that simplifies the calculation.
However things are not in such a happy state for the nucleus. Quantum mechanics still governs its behavior but the force law is more complicated. There is not a natural force center; we are dealing with a many body problem of great complexity. In the absence of comprehensive nuclear theory we turn to the construction of nuclear models.

Two models of the nucleus have proved to be useful:

1. The Liquid Drop Model - in this model the nucleons are imagined to interact strongly with each other, like molecules in a drop of liquid. A given nucleon collides frequently with each other nucleons, its mean free path as it moves about, being substantially less than the nuclear radii. This model is useful for explanation of a large class of nuclear reactions (for example nuclear fission).
2. The Independent Particle Model is based on the assumption that each nucleon moves in a well-defined orbit within the nucleus and hardly makes any collisions at all. A nucleon in a nucleus, like an electron in an atom, has a set of quantum numbers that define its state of motion.

7.1 Nuclear Terminology

Nuclei are made up from protons and neutrons. We represent the number of protons in the nucleus - called the atomic number (or the proton number) of the nucleus by the symbol Z and the number of neutrons - the neutron number by the symbol N.
The total number of neutrons and protons in a nucleus is called its mass number A, so that

$$A = Z + N \tag{7-1}$$

Neutrons and protons, when considered collectively are called nucleons. We represent nuclides by symbols as

$${}^{A}_{Z}\mathrm{X} \quad \text{or} \quad \mathrm{X}^{A}_{Z} \quad \text{or} \quad \mathrm{X}A,$$

where X stays for the chemical symbol, superscript A stays for mass number and subscript Z stays for atomic number.
Thus for example ${}^{4}_{2}\mathrm{He}$ tells us that this element is helium whose mass number is 4 and atomic number is 2.
Nuclides with the same atomic number Z but different neutron numbers N are called **isotopes**. The neutral atoms of all isotopes for a given Z have the same number of external electrons and the same chemical properties. The elements, which we meet in nature, are usually a mixture of different isotopes.
As an example of isotopes let us have a look on hydrogen, which has three isotopes:

- ${}^{1}_{1}\mathrm{H}$ - the nucleus contains one proton.
- ${}^{2}_{1}\mathrm{H}$ - the nucleus contains one proton and one neutron - deuterium.

- ${}_1^1H$ - the nucleus contains one proton and two neutrons - tritium.

Nuclear radii

A convenient unit for measuring distances on the scale of nuclei is the femtometer. The unit is often called the fermi. Thus we have

$$1 \text{ femtometer} = 1 \text{ fermi} = 1 \text{ fm} = 10^{-15} \text{ m}.$$

The experiments with bombardment of nuclei with high-energy electrons show that the nucleus (assumed to be spherical) has a characteristic mean radius given by

$$R \cong 1.5 \times 10^{-15} A^{1/3} \text{ m}. \tag{7-2}$$

In this expression A is the mass number. We see that the volume of the nucleus, which is proportional to R^3 is directly proportional to the mass number A, being independent of the separate values of Z or N.

Nuclear masses are given in atomic mass units (abbreviation u) chosen so that the atomic mass of C12 is exactly $12u$. The relation of this unit to the SI mass unit is

$$1\ u = 1.661 \times 10^{-27} \text{ kg}.$$

The mass number of nuclides is so named because the number represents the mass of the nuclide expressed in atomic mass units. Thus the atomic mass of any nuclide is

$$m = A\ u. \tag{7-3}$$

Using Eq.7-2 and Eq.7-3 we can determine the mass density of the nucleus as

$$\rho = \frac{m}{V} = \frac{Au}{\frac{4}{3}\pi R^3} = \frac{Au}{\frac{4}{3}\left(1.5 \times 10^{-15} A^{1/3}\right)^3} \approx 2 \times 10^{17} \text{ kgm}^{-3}.$$

We can see that the mass density of the nucleus is the immense number, which is caused by the fact that the radius of the nucleus is negligibly small and almost all the mass of the atom is concentrated in it.

Nuclear binding energy

The total energy required to tear apart the nucleus into its constituent protons and neutrons can be calculated from Einstein's relation $E = \Delta m c^2$ and is called the nuclear binding energy. We can express Δm as

$$\Delta m = \left[Zm_p + (A - Z)m_n\right] - M_{nucleus}, \tag{7-4}$$

where m_p is the mass of proton and m_n is the mass of neutron. If we divide the binding energy of a nucleus by its mass number we get the binding energy per nucleon.

The curve of the binding energy per nucleon as a function of mass number A is shown in Fig. 7-1. The fact that this binding energy curve "droops" at both high and low mass numbers has practical consequences of the greatest importance.

The drooping of the binding energy curve at high-mass numbers tells us that nucleons are more tightly bound when they are assembled into two middle mass nuclides rather than into a single high mass nuclide. In other words the energy can be released by the nuclear fission of a single massive nucleus into two smaller fragments.

The drooping of the binding energy curve at low-mass numbers tells us that energy can be released if two nuclides of small mass number combine to form a single middle mass number nuclide. This process, the reverse of fission, is called nuclear fusion. It occurs inside our sun and in thermonuclear explosions. Controlled nuclear fusion as a practical energy source is a subject of intensive research.

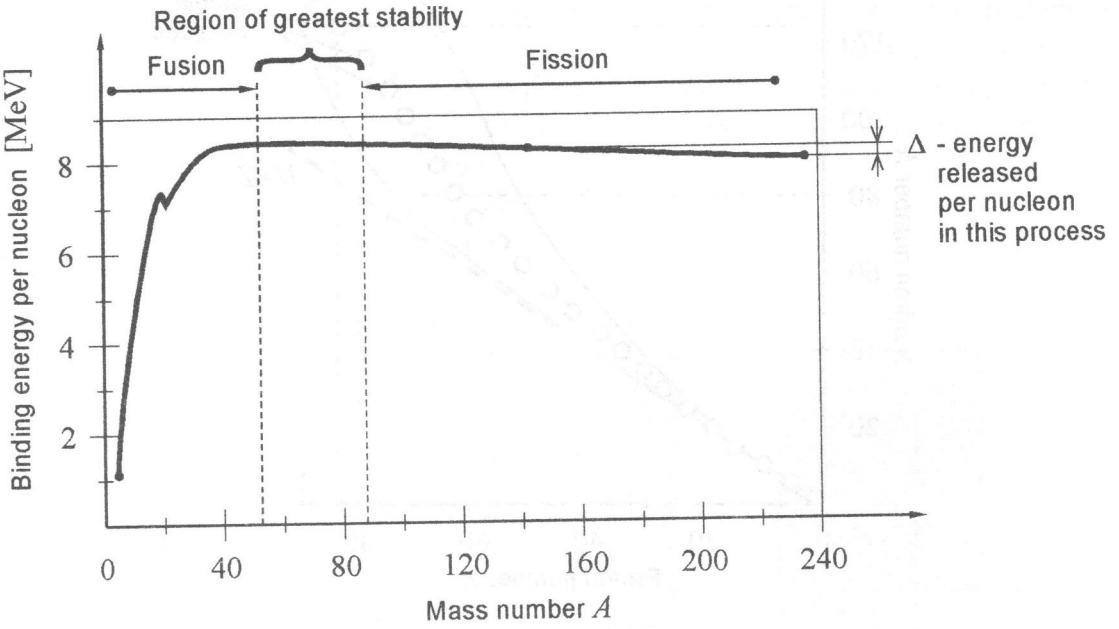


Figure 7-1

Nuclear force

Perhaps you have wondered how protons can be bound together in a nucleus. After all like charges do repel each other. There is indeed a strong electrostatics force acting to push the protons apart, but there is also another force many times stronger that acts to hold them together inside a nucleus. This force is called a **strong nuclear force** – one of the four fundamental forces in nature.

Compared to the gravitational and electromagnetic forces the strong nuclear force is rather strange. It is much stronger than the others, but it has an extremely short range: the attractive nuclear force between particles in the nucleus effectively disappears if the particles become more than about 3×10^{-15} m apart. This puts an upper limit on the size that a nucleus can have and still be stable. In a large nucleus protons on opposite sides are far enough apart that the repulsive force becomes important. No known stable isotopes has an atomic number larger than 83.

Another interesting feature of the strong nuclear force is that it does not depend on the electric charge.

The strong nuclear force has also the saturation properties. Thus the effectiveness of this force at holding a nucleus together also depends on the relative number of neutrons and protons. If there are too many neutrons compared to the number of protons, the nucleus will not be stable.

Nuclidic chart

The neutral atoms of all isotopes for a given proton number Z have the same number of external electrons, the same chemical properties, and fit into the same box in the periodic

table of the elements. The nuclear properties of the various isotopes, however, are very different. Thus the periodic table of the isotopes is of limited use to the nuclear physicists. Therefore we organize the nuclides on a nuclidic chart, see Fig. 7-2, in which a nuclide is represented by plotting its neutron number N against its proton number Z.

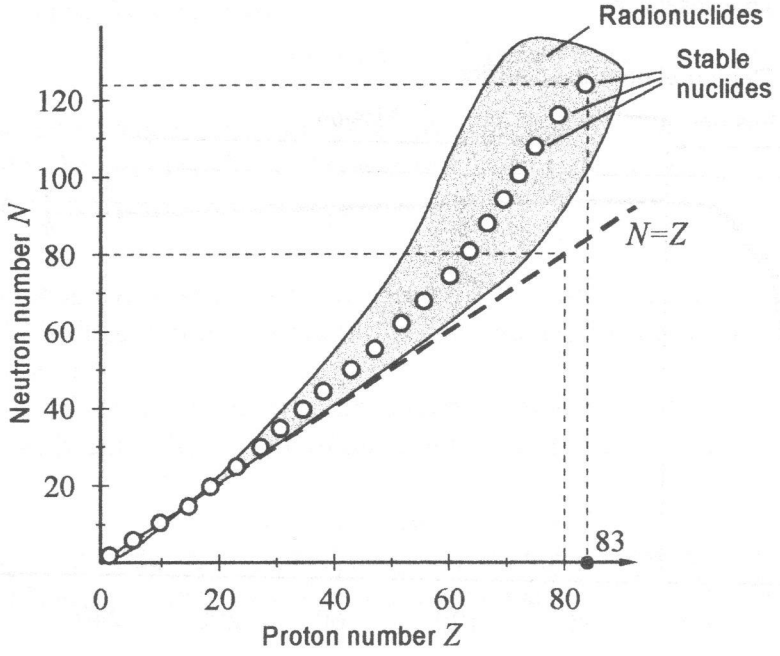


Figure 7-2

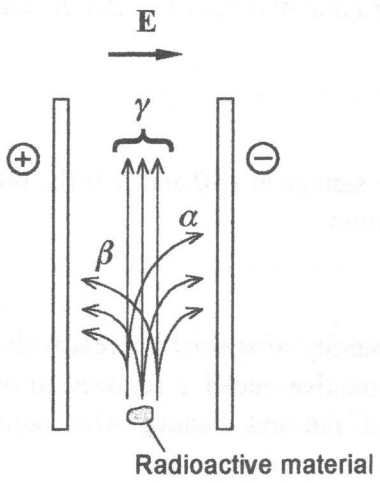
Each dot in this figure represents one stable isotope. The solid line indicates the nuclei that would have the same number of protons and neutrons. Note that light stable nuclides ($N < 20$) tend to lie close to the $N = Z$ line, which means that they have the same number of neutrons and protons. Heavier nuclide, however, tend to have more neutrons than protons. As far as these heavier nuclides have an increasingly larger excess of neutrons, and the nuclear force is limited to its ability to hold nucleons together, these nuclides are unstable, they eject particles and release energy. The figure shows that there are no stable nuclides with proton number $Z > 83$ (bismuth). All nuclides with proton number $Z > 83$ decay spontaneously. This effect is known as radioactivity.

7.2 Natural Radioactivity

Radioactivity, also called radioactive decay, occurs when an unstable nucleus emits radiation. Isotopes with unstable nuclei are called radioisotopes. The majority of all isotopes are radioactive.

It was soon determined that there were actually three different types of nuclear radiation, named alpha (α), beta (β) and gamma (γ) radiation.

Suppose that a piece of radioactive material is placed into the electric field. We see that α and β rays are deflected by the electric field whereas the γ rays are not deflected. The α- particles are deflected toward a negatively charged electrode, therefore α-particles have positive charge. It was shown that α-particle consists from two protons and two neutrons. It is identical to a nucleus of helium ${}_2^4He$.



The alpha particles are ejected with very high speeds (typically around one-twentieth the speed of light). Alpha particles are quickly absorbed when they enter matter – even a sheet of paper can stop them (see Fig. 7-4).
From Fig. 7-4 we see that β-particles are deflected toward a positively charged electrode. A β-particle is simply an electron ejected from a nucleus with a speed about 0.9 speed of light.

Figure 7-3

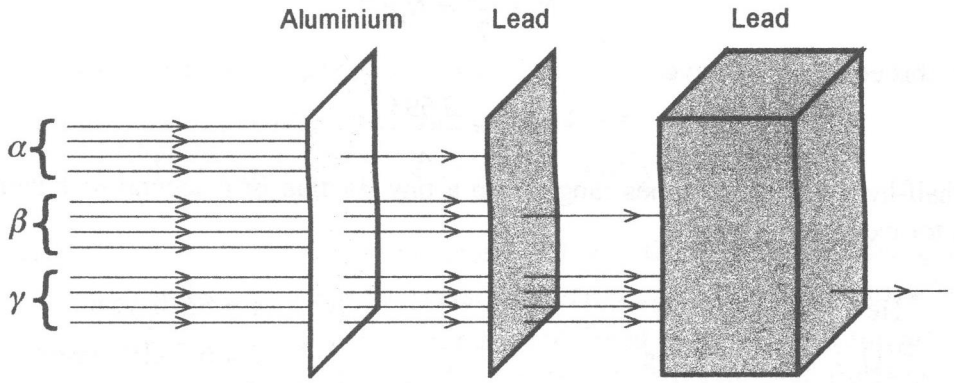


Figure 7-4

β-particles are more penetrating than α-particles. For comparison, a thin sheet of aluminium that will block essentially all α-particles will stop only a fraction of β-particles.
From Fig. 7-3 we see that γ-radiation is not deflected by the electric field. We conclude that γ-rays have no electric charge, they are extremely high-frequency electromagnetic waves. The γ-rays are the most penetrating of the three. Since they have no electric charge and travel at the speed of light they interact with atoms much less frequently. It requires several centimeters of lead to block γ-rays (see Fig. 7-4).

7.3 Radioactive Decay

Most of the nuclides that have been identified are radioactive. That is a given nucleus spontaneously emits a particle, transforming itself into a different nuclide. The theory that describes the radioactive decay is a statistical theory, which means that radioactive decay is a random process.
Let the sample contain N radioactive nuclei at time t. The number of nuclei ($-dN$) that transforms during the time dt is proportional to this time dt, to the original number N of nuclei and so called disintegration constant λ, which has a characteristic value for every radionuclide, or

$$-dN = \lambda N dt \,. \tag{7-5}$$

In Eq. 7-5 the negative sign expresses the fact that original number of nuclei decreases. We separate variables and we integrate

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt,$$

where N_0 denotes number of radioactive nuclei in the sample at $t=0$ and N is the number of remaining nuclei at any subsequent time. Thus we obtain

$$N = N_0 e^{-\lambda t}. \tag{7-6}$$

This equation is called **exponential decay law**. A quantity of special interest is the **half-life** τ defined as the time after which the number of radioactive nuclei is reduced to one half of its initial value. Let us find relationship between half-life and disintegration constant. For time $t=\tau$ we can write

$$N = \frac{N_0}{2} = N_0 e^{-\lambda t}.$$

From this equation we have

$$\tau = \frac{0.693}{\lambda}. \tag{7-7}$$

The half-lives of radioisotopes range from a tiny fraction of a second to billions of years. Thus for example

${}^{5}_{2}\mathrm{He}$	$\tau = 2\times10^{-21}$ s	${}^{14}_{6}\mathrm{C}$	$\tau = 5370$ years
${}^{237}_{92}\mathrm{U}$	$\tau = 6.75$ days	${}^{238}_{92}\mathrm{U}$	$\tau = 6.5\times10^{9}$ years.

7.4 Equilibrium Condition - Radioactive Series

It should be noted that in a typical radioactive decay there are several related radioactive nuclei decaying successively into each other by α decay (and/or other decay processes). For example ${}^{234}_{92}\mathrm{U}$ α decays into ${}^{230}_{90}\mathrm{Th}$ which α decays into ${}^{226}_{88}\mathrm{Ra}$ etc. Thus a system initially filled with ${}^{234}_{92}\mathrm{U}$ will eventually contain a mixture of all these nuclei.

Let us derive now the differential equation governing the general behavior of such a family. Consider a family of decays in which the parent has the longest lifetime. The population of the first daughters is constantly re-supplied from decay of the parent and on the other side the first daughters decay after they are formed. Thus we can write for the number of nuclei dN_2 of the first daughter

$$dN_2 = \lambda_1 N_1 dt - \lambda_2 N_2 dt, \tag{7-8}$$

where

- $\lambda_1 N_1 dt$ - is the increase of number of nuclei of the first daughter caused by decay of N_1 of nuclei of parent,
- $\lambda_2 N_2 dt$ - is the decrease of number of nuclei of the first daughter caused by its decay.

We can write similar equation for the second daughter since they are formed at a constant rate from the decay from the first daughter etc.

In fact the number of nuclei of all the daughters will remain constant, otherwise the number of nuclei of some daughter will increase, which is in contradiction with reality. Thus we can write an equilibrium condition

$$\frac{dN_2}{dt} = 0 \qquad \text{or} \qquad \lambda_1 N_1 = \lambda_2 N_2 . \tag{7-9}$$

Taking into account Eq. 7-7 we can rewrite this equilibrium condition as

$$\frac{N_2}{N_1} = \frac{\tau_2}{\tau_1} . \tag{7-10}$$

This equation can be used for example to determine the values of τ, from measurements of N and one known τ.

We can now understand how α-decaying nuclei with very short lifetimes can be found in nature. For example $^{212}_{84}\mathrm{Po}$ with $\tau \sim 10^{-6}\,\mathrm{s}$, can be extracted from naturally occurring minerals that presumably have been in existence for billions of years. The reason is that short lifetime α emitters are in equilibrium in decay families with long lifetime parents. These families are called radioactive series. There are three such series that occur naturally:

- the $4n$ series whose parent is $^{232}_{90}\mathrm{Th}$ with $\tau = 2.01\times10^{10}$ years,
- the $(4n+2)$ series whose parent is $^{238}_{92}\mathrm{U}$ with $\tau = 6.52\times10^{9}$ years,
- the $(4n+3)$ series whose parent is $^{235}_{92}\mathrm{U}$ with $\tau = 1.02\times10^{9}$ years.

There is evidently also room for a $(4n+1)$ series. Actually there is such a series, whose parent is $^{237}_{93}\mathrm{Np}$ with lifetime $\tau = 3.25\times10^{6}$ years. This series can be produced artificially by using a nuclear reaction to make the parent, but it is not found in nature since the lifetime of the parent is very short compared to the age of the earth, which is estimated from geological evidence to be about 10^{10} years.

The names of the series characterize the mass number A for the members of the series. For instance, the parent of the $(4n+3)$ series has A equal to four times an integer plus three, where the integer is 58.

The series $4n$, $(4n+2)$, and $(4n+3)$ end with a stable isotope of Pb while the $(4n+1)$ serie ends with $^{209}_{83}\mathrm{Bi}$.

7.5 Measuring of Radiation Dosage

We are constantly exposed to small amount of nuclear radiation. The natural sources of radiation that people have always been exposed to include cosmic radiation from outer space, radioisotopes in the soil and rocks, radioisotopes in the human body (like carbon-14 and potassium-40) and in the air we breath. In the last century human activity has added to these natural sources of radiation a number of other sources. They include medical and dental x-rays, radioisotopes released by nuclear research activities, the production of nuclear power industry and traces of radioactive fallout from nuclear weapons testing. There are also accidents in nuclear research laboratories, nuclear material processing facilities and nuclear reactors (such as Chernobyl power plants accidents in 1986). Massive doses of nuclear radiation can be harmful and, if large enough, fatal.

Nuclear radiation damages living tissue because it is ionizing radiation. It ionizes atoms along its path as it travels through matter. Inside living cells this ionization can break up molecules, thereby killing the cell or affecting its ability to reproduce. The resulting damage to the living organism can be classified as somatic or genetic.

Somatic effects are direct injury to the organism itself. In the course of normal maintenance, the body replaces millions of dead cells each day. But if radiation kills too many cells, the body can not keep up, and radiation sickness results. This is characterized by nausea, fatigue, loss of hair, reddening of the skin an other symptoms. Even if a cell is not killed, radiation damage to molecules in a gene inside the cell causes a mutation. Since genes control the cell's ability to reproduce itself, mutations can lead to abnormal cell growth and cancer.
Clearly it is important to be able to measure radiation doses and to know what levels are potentially harmful. There are several quantities that describe the properties and effects of nuclear radiation.

The activity
The activity (decay rate) – of a radioactive source is defined as a number of disintegrations per second. The unit of activity is 1 **becquerel** (abbr. Bq).

$$1 \text{ Bq} = 1 \text{ disintegration per second.}$$

We still can meet with older unit of activity called the **curie** (abbr. Ci). It is defined as

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ disintegrations per second.}$$

The number 3.7×10^{10} has been chosen because it corresponds to the number of disintegrations per second in 1g of radium-226.
Differentiating Eq.7-6 we can obtain the dependence between activity of the source and time

$$dN = -N_0 \lambda e^{-\lambda t} dt .$$

Denoting

$$R = -\frac{dN}{dt} = \lambda N_0 e^{\lambda t},$$

we can write

$$R = R_0 e^{\lambda t}, \qquad (7\text{-}11)$$

where $R_0 = \lambda N_0$ is the activity at time $t = 0$ and R is the activity of the source at any subsequent time t.

The radiation absorbed dose
A measure of the dose actually absorbed by a specific object in terms of the energy transferred to it was measured with units called the **rad** – Radiation Absorbed Dose. An object is said to have received an absorbed dose of 1 rad if each kilogram of the object absorbed 0.01 J of energy from the radiation, or

$$1 \text{ rad} = 0.01 \text{ J/kg.}$$

The present unit of radiation absorbed dose is called the **gray** (abbr. Gy). This unit is defined as

$$1 \text{ Gy} = 1 \text{ J/kg.}$$

The dose equivalent
The different types of ionizing radiation do not have the same ability to cause harmful effects. Therefore we introduce the dose equivalent, the unit of which is the **sievert** (abbr. Sv). The dose equivalent is fond by multiplying the radiation absorbed dose (in grays) by a Relative Biological Effectiveness (RBE) factor, or

$$[\text{Sv}] = [\text{RBE}] \times [\text{Gy}].$$

The RBE factor may be found in tabulated in various reference sources. Thus for example:

Gamma rays, β-particles	RBE ≈1
Slow neutrons	RBE ≈5
α-particles	RBE≈20.

It is therefore seen that 1 Gy of alpha radiation tends to do more harm than 1 Gy of gamma radiation.

What levels of radiation are harmful? Since some of the somatic effects like cancer and leukaemia may not show up in a victim for decades and since some genetics effects may not show up for a century or more it is difficult to determine what is the highest dose that will not cause any harm. Studies of accidents and bomb victim do give us fairly good idea of massive doses of radiation.

Doses below	0.25 Sv	no immediate effects.
Doses about	1 Sv	mild radiation sickness.
Doses about	5 Sv	fatal about 50% of the time.
Doses about	8 Sv	almost always fatal.

The average dose from natural sources of radiation is about 1.3×10^{-3} Sv per year.

7.6 Alpha, Beta and Gamma Decay

A process that is particularly important in radioactive decay is α decay, occurring commonly in nuclei with atomic number $Z > 83$. It involves the decay of an unstable parent nucleus into its daughter nucleus by the emission of an α particle, that is the nucleus of ${}^{4}_{2}\text{He}$ The process takes place spontaneously because it is energetically favored, the mass of the parent nucleus being greater than the mass of the daughter nucleus plus the mass of the α-particle. The energy made available in the decay is the energy equivalent of the mass defect. This decay energy E is carried away by the α particle as kinetic energy. Thus for example the radionuclide ${}^{238}_{92}\text{U}$ decays according to the scheme

$$ {}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} \qquad E = 4.25 \text{ MeV}. \tag{7-13}$$

The half-life of this radionuclide is 4.5×10^{9} years. A natural question is why did the ${}^{238}_{92}\text{U}$ nuclei not decay shortly after they were created? Why did they wait so long? To answer these questions we have to return to quantum mechanical problem of barrier penetration, see chapter 6-9.6.

We choose a model in which the α-particle is imagined to exist preformed inside the nucleus before it escapes. Fig. 7-5 shows a potential energy function $V(r)$ describing the emission of α-particle by ${}^{238}_{92}\text{U}$ following the scheme given by Eq.7-13.

It is a combination of a potential well associated with the attractive strong nuclear force that acts in the nuclear interior and a Coulomb potential associated with the repulsive electrostatic force that acts between the two particles after the decay has occurred.

The horizontal line marked E = 4.25 MeV shows the decay energy for the process. This line is shown hatched in the region in which it lies under the potential energy curve. If the α-particle found itself in that region, its potential energy V would exceed its total energy E, which would mean, classically, that its kinetic energy $E_K = E - V$ would be negative.

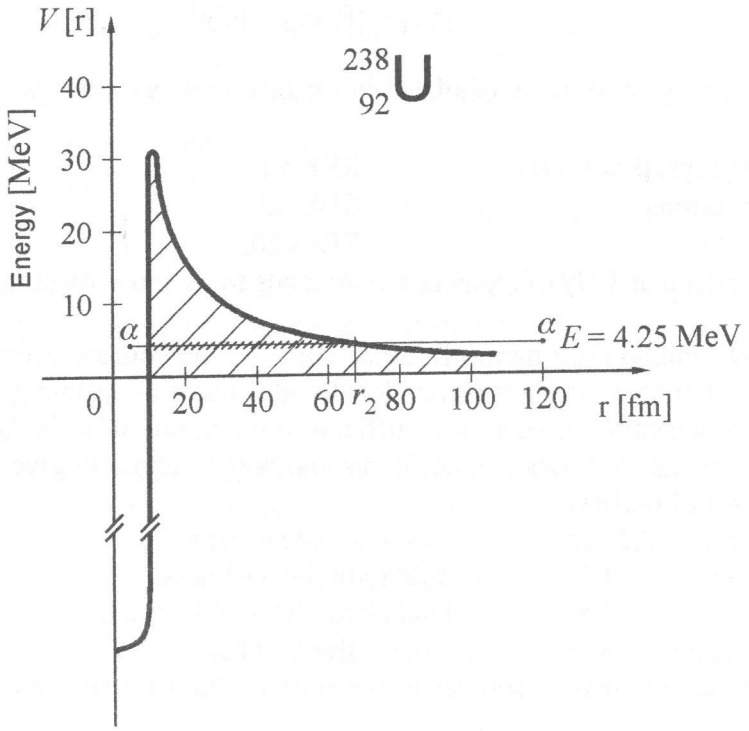


Figure 7-5

Obviously this is an impossible situation. In this figure the α-particle is represented by a dot, both inside the barrier and outside of it, after it has tunneled through.

From Fig. 7-5 we see why the α-particle is not immediately emitted from a $^{238}_{92}U$ nucleus. It is because the nucleus is surrounded by a high potential barrier. The particle can however tunnel through a barrier that is classically insurmountable. The transmission coefficient T for the barrier potential problem is given by Eq.6-111. This expression was derived for a rectangular barrier of height V_0 and width a. However, it can be applied to the barrier shown in Fig. 7-5 by considering it to be a set of adjacent rectangular barriers of height $V(r_i)$ and a very small width Δr_i. This reasoning leads in the limit to the integral over dT_i, where the integration is taken from the nuclear radius r_1, where $V(r)$ rises above E, to the radius r_2, where $V(r)$ drops below E.

The transmission coefficient gives the probability that in one trial α-particle will penetrate the barrier. The number of trials per second could be estimated to be

$$N \approx \frac{v}{2r_1}, \tag{7-14}$$

if it were assumed that α-particle is rattling back and forth within the nucleus of diameter $2r_1$ with velocity v. We assume that this velocity is comparable to the velocity of the α-particle after emission $E = \frac{mv^2}{2}$.

We can therefore express the probability per second that the nucleus will decay by emitting an α-particle, called decay rate R (see Eq.7-11) as the product of the number of trials per second and transmission coefficient. Gamow and Condon used this result to determine decay rates and consequently half-lives of different radioactive nuclei. They obtained values, which were in good agreement with those measured experimentally, although the half-lives vary over a tremendously large range. Thus for example the half-life of $^{238}_{92}U$ is

4.5×10^9 years. For an extreme contrast consider α decay of other uranium isotope $^{228}_{92}U$ which has a decay energy E = 6.81 MeV, higher than that of $^{238}_{92}U$. The transmission coefficient of the barrier is very sensitive to the total energy of the particle seeking to penetrate it. The height of the barrier and the nuclear radius do not change significantly for nuclei in the limited range of the periodic table in which α emitting nuclei are found. Thus we expect α decay to occur more readily for $^{228}_{92}U$ then for $^{238}_{92}U$. Indeed the half-life of $^{228}_{92}U$ is only 9.1 minutes. We see that an increase in energy of the α-particle by a factor of only 1.6 produces a decrease in half-life by a factor of about 3×10^{14}. The explanation of α decay is a great success of Schrodinger's quantum mechanics.

A nucleus that decays spontaneously by emitting an electron (or positron) is said to undergo beta decay. This, like α decay, is a statistical process, governed by Eq. 7-6 and Eq. 7-12. Here are two examples of β decay:

$$^{32}_{15}P \rightarrow {}^{32}_{16}S + e^- + \nu, \tag{7-15}$$

and

$$^{30}_{15}P \rightarrow {}^{30}_{14}Si + e^+ + \nu. \tag{7-16}$$

The symbol ν represents a neutrino, a massless, neutral particle that is emitted from the nucleus. The symbol e^- is an electron and e^+ is the antiparticle to an electron called positron. Both electric charge and nucleon number are conserved in the above two processes.

It may be surprising that nuclei can emit electrons and neutrinos since we know that nuclei are made up of neutrons and protons only. Both these particles are created during the emission process, a neutron transforming itself into a proton within a nucleus (or conversely) according to

$$n \rightarrow p + e^- + \nu, \tag{7-17}$$

or

$$p \rightarrow n + e^+ + \nu. \tag{7-18}$$

Unlike α decay, where every emitted α-particle has the same sharply defined energy in β decay the disintegration energy is shared – in varying proportions – between the electron and the neutrino. Thus in β decay the energy of the emitted electrons is distributed in a continuous spectrum from zero up to a certain maximum.

The neutrino hypothesis, presented by Pauli in 1930, not only permitted an understanding of the nature of continuous electron spectrum but also solved the problem of conservation of the angular momentum law. The neutrino is a truly elusive particle – the mean free path of the energetic neutrino in water is greater than several thousands of the light years. Even the earth is totally transparent to neutrinos emitted by the sun. In spite of their elusive character, neutrinos were detected in the laboratory in 1953.

Since a gamma rays have not mass or electric charge, γ ray emission has no effect on the mass number A or the atomic number Z of a nucleus. Nuclei can exist in excited states in much the same way that orbiting electrons can. Gamma rays are emitted when the nucleus goes into a lower energy state. Most typically γ decay will arise when the preceding β decay has produced some of the daughter nuclei in states of several MeV excitation. Thus α and β radiation is frequently accompanied by γ radiation.

The example is strontium 87 undergoing γ decay

$$^{87}_{38}Sr^* \rightarrow {}^{87}_{38}Sr + \gamma. \tag{7-19}$$

In this equation the asterisk indicates that the nucleus is in excited state. The identity on the nucleus is not changed during the process.

7.7 Artificial Nuclear Reactions

Radiaoactivity is an example of a natural nuclear reaction. With the exception of gamma decay, each of these results in transmutations – the conversion of an atom of one element into an atom of another element. Many types of nuclear reactions can be induced artificially in laboratories. A common example is the bombardment of nuclei with alpha particles, beta particles, neutrons, protons or other nuclei. If a nucleus "captures" the bombarding particle, it will become a different element or isotope.
The first artificial reaction, which was produced by Rutherford in 1919, involved the bombardment of nuclei of nitrogen with alpha particles (E = 7.7 MeV). The result is oxygen, following this scheme

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{16}_{8}\mathrm{O} + ^{1}\mathrm{H}. \qquad (7\text{-}20)$$

It should be pointed out that for any nuclear reaction the conservation laws must be fulfilled. By way of summary we can list following laws:

In any nuclear reaction the following quantities must be conserved:

- Number of nucleons.
- Charge.
- Total relativistic energy.
- Linear momentum.
- Angular momentum.
- Parity.

Thus for example the law of conservation of the number of nucleons tells us that the total number of nucleons before the reaction must be equal to the total number present after.
As an example we use these laws to find the residual nucleus in the reaction in which a proton $^{1}_{1}\mathrm{H}$ is a bombarding particle, a neutron $^{1}_{0}\mathrm{n}$ is the product particle, and $^{9}_{4}\mathrm{Be}$ is the target nucleus. The reaction is

$$^{1}_{1}H + ^{9}_{4}Be \rightarrow ^{A}_{Z}X + ^{1}_{0}\mathrm{n}, \qquad (7\text{-}21)$$

where $^{A}_{Z}\mathrm{X}$ represents the unknown residual nucleus. Conservation of charge requires that the sum of values of atomic numbers Z on the left side of the reaction formula equal the sum of the Z values on the right side. That is

$$1 + 4 = Z + 0, \quad \text{or} \quad Z = 5.$$

Conservation of the number of nucleons requires that the sum of the values of mass numbers A on the left side equals the sum of the A values on the right side. Therefore we have

$$1 + 9 = A + 1, \quad \text{or} \quad \mathrm{A} = 9.$$

Thus we have identified the residual nucleus as $^{9}_{5}\mathrm{B}$ and the reaction is

$$^{1}_{1}\mathrm{H} + ^{9}_{4}\mathrm{Be} \rightarrow ^{9}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n}. \qquad (7\text{-}22)$$

Another example of an artificial nuclear reaction is that which was used in 1932 by Chadwick. This reaction which led to the discovery of the neutron is described by following scheme

$$^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \rightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}\mathrm{n}. \qquad (7\text{-}23)$$

One example of a useful artificial reaction involves bombardment of uranium 238 nuclei with neutrons. The result is uranium 239.

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U}\,. \qquad (7\text{-}24)$$

This new nucleus undergoes two beta decays, resulting in plutonium 239:

$$^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}$$
$$^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e} \qquad (7\text{-}25)$$

Plutonium 239 (half-life 2.46×10^{4} years) can be used directly in nuclear reactors, but the original uranium 238 can not. A breeder reactor is a nuclear reactor designed to use neutrons to produce, or "breed" the reactor fuel plutonium 239.

The subject of artificial nuclear reactions is a vast one because there are so many different types of reactions. Any stable nuclear particle can be the bombarding particle, any stable nucleus can be the target nucleus. Wide variety of particles can be emitted from the reaction as product particles. These particles, stable or radioactive, could be used for various purposes.

One of the interesting applications of artificial radioactivity is neutron activation analysis. This is an accurate method for determining what elements are present in a substance. The material to be tested is bombarded with neutrons. Many of the nuclei of the substance are transformed into radioisotopes. By monitoring the radiation that is then emitted, it is possible to determine which elements were originally present. For example the only naturally occurring isotope of sodium, sodium 23, becomes radioactive sodium 24 by neutron absorption

$$^{23}_{11}\mathrm{Na} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{24}_{11}\mathrm{Na}\,. \qquad (7\text{-}26)$$

Sodium 24 emits both gamma and beta rays with specific energies. If sodium is present in an unknown substance, it can be detected by bombarding the substance with neutrons and then looking to see whether gamma and beta rays with the proper energies are emitted.

Neutron activation analysis has been used to make some interesting discoveries. An analysis of lock of Napoleon Bonaparte's hair revealed a high concentration of arsenic. Napoleon may have been poisoned, a possibility that was revealed by neutron activation analysis a long time after his dead.

Neutron activation analysis is used in some airports to search luggage for explosives. Nitrogen is abundant in most chemical explosives. The bomb detector irradiates luggage with neutrons and then looks for the characteristic radiation emitted by nitrogen that could indicate the presence of explosives.

Artificial radioisotopes are also used in medicine. In nuclear medicine small amounts of radioactive material are introduced into the body as diagnostic tool. Images can be produced that show the distribution of the radioactive substance in different parts of the body. Thus we obtain physiological information about the amount of radioactive pharmaceutical substance that has lodged in the organ of interest. There are many radioactive nuclei that might be used for diagnostic study. Two commonly used isotopes are technetium 99 and iodine 131. Technetium has a half-life of 6 hours and emits 140 keV gamma rays. Attaching it to a chemical with the desired pharmacological properties controls the site within the body to which the technetium will go. For example it can be attached to tiny microspheres of albumin to study blood flow in capillaries or it can be combined with organic phosphorous for bone studies etc. All ionizing radiation may damage tissue, and x-ray or nuclear medicine procedures should not be carried out indiscriminately. However, they provide essential information in a relatively safe and comfortable manner.

7.8 Detectors of Particles

Since subatomic particles are too small to observe and measure directly, their properties must be determined through the effects they produce. The development of devices that measure such effects has made the study of nuclear interactions one of the most important branches of modern physics.

The operation of detection instruments depends on three main characteristics of the particles and rays emitted in nuclear reactions:

- They have the ability to ionize certain substances.
- They cause certain substances to fluorescent.
- They affect photographic emulsions.

Geiger counter

Instruments that make use of ionization effects are Geiger counter, the cloud chamber, the bubble chamber, the spark chamber and the ionization chamber. The scintillation counter is based on the principle of fluorescence. Photographic emulsions are used both as a direct means of detection and in conjunction with other instruments.

The principle of ionization is used in Geiger counter, see Fig. 7-6. A hollow cylinder acts as a negative electrode and a thin wire down the center is charged positively. The tube is filled with a gas at low pressure and a potential difference of about 1000 V is applied to the electrodes. This is slightly less than the voltage required to ionize the gas and to enable it to conduct an electric current between the electrodes. When a charged particle or gamma ray enters the Geiger tube, it knocks electrons from the gas atoms in its path and produces ions.

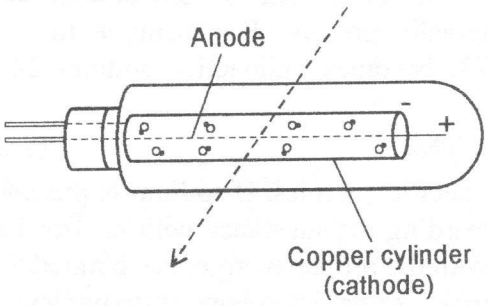


Figure 7-6

These electrons are then attracted to the positively charged wire. As they move in the direction of the wire, they collide with more gas atoms to produce additional free electrons and positive ions. Eventually, the surge of electrons toward the positive electrode is large enough to start the current flowing through the tube. Thus the Geiger tube acts as its own amplifier for the detection of nuclear events. In addition, the instrument can be used in conjunction with external circuits to activate flashing lights, a loudspeaker, or a counting device.

Spark chamber

The discharge in an ionization chamber can also be made directly visible through the arrangement like the one shown in Fig. 7-7. The positive and negative electrodes are placed in series in this device. When a particle or ray triggers a current in such a spark chamber, its path becomes visible as a series of light flashes. These flashes can be easily photographed to provide permanent records.

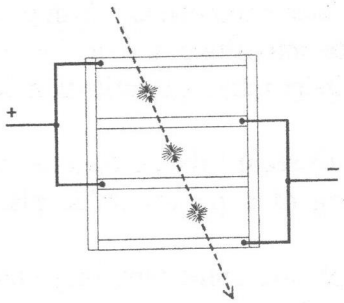


Figure 7-7

Diffusion cloud chamber

The diffusion cloud chamber is another device that makes the paths of ionizing particles and rays visible. In the chamber there is an alcohol which evaporates and condenses again as it reaches the cold region at the bottom of the chamber. Just above the floor of the chamber there is a region where the alcohol vapor does not condense unless there are „seeds" around which drops of alcohol can form.

If there is no dust in the chamber, the only seeds available are ions produced by the passage of charged particles or rays. The resulting tray of alcohol droplets is then visible against the black bottom of the chamber and can be photographed. Others types of chambers, including the chamber developed by Wilson, relay on pressure changes instead of low temperatures to produce condensation. It is possible to use many other liquid-vapor arrangements to produce the tracks. But in all cloud chambers, it is the ionizing effect of high-speed particles and rays that makes a visible trail possible.

Bubble chamber

In a cloud chamber a substance like alcohol condenses from a gas to a liquid to make nuclear events visible. In a bubble chamber, exactly the opposite principle is used. A container is filled with a liquid and the tracks of particles become visible as series of bubbles when the liquid boils.

One substance used in a bubble chamber is liquid hydrogen. As long as the temperature and pressure conditions are right, the hydrogen stays in liquid form. But if the pressure is suddenly lowered, the hydrogen boils violently. If, at the same instant, high-speed particles or rays are allowed to pass through the hydrogen, ions are formed. The hydrogen boils a few thousandths of a second sooner around these ions than in the rest of the chamber. Carefully timed photos are used to record the resulting bubble trails.

The advantage of the bubble chamber over the cloud chamber is that more nuclear collisions take place in the dense liquid of the bubble chamber. This makes it possible to study particles and rays having speeds that are much higher than those which produce recordable events in a cloud chamber.

Scintillation chamber

In this device alpha and beta particles from radioactive materials or nuclear reactions strike a zinc sulphide screen.

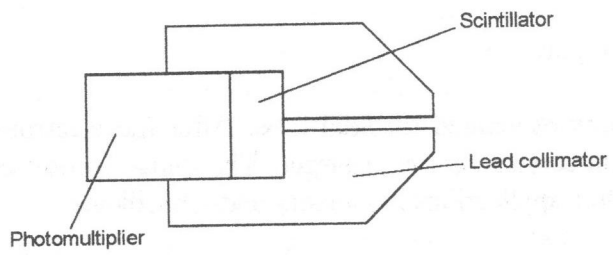


Figure 7-8

When these particles strike the screen they produce a momentary flash of light. By counting a number of flashes in a given period of time, the intensity of a radiation may be determined. The scintillation counter uses also a photomultiplier tube. A scintillation detector used in a nuclear medicine is shown in Fig. 7-8.
The photographic emulsions can also be used to record the passage of subatomic particles and rays directly. In fact, it was the fogging of a photographic plate that led to the discovery of radioactivity by Becquerel..
When charged particles or gamma rays strike photographic film, they change the chemicals on the emulsion such the same way that a ray of light changes them. Upon developing the film the passage of the particle or a ray is recorded as a spot. If a series of photographic plates is exposed to a nuclear event, the history of the event is recorded as a series of streaks through the stack of plates. This method is one of the most direct and most useful detection techniques in particle physics.

7.9 Particle Accelerators

As we have seen nuclear reactions can be caused by particles and rays from natural radioactive substances. But the nuclear research that can be conducted in this way is limited by the energy of the radioactive emissions. To provide elementary particles with energies of the order up to 10^{12} eV it is necessary to accelerate them in some way.
One of the earliest particle accelerators was developed by Van der Graaf in 1931. Electrons are sprayed on an insulated moving belt by repulsion from the strongly negative electrode. They side up on the belt to the top of the generator where they are picked of by a collector. Thus a large negative charge is built up on the top terminal. Van der Graaf generators provide energies ranging up to about 20 MeV depending on the nature of the accelerating particles.
Shortly after the development of the Van der Graaf generator it was found that charged particles could be accelerated to very high velocities by driving them in a circular path by means of electromagnets. A variety of such accelerators have been built since then.

Betatron
The betatron is used to accelerate beta particles - electrons. It uses the principle of the transformer, in which the primary is a huge electromagnet and the secondary is the stream of electrons being accelerated, see Fig. 7-9.

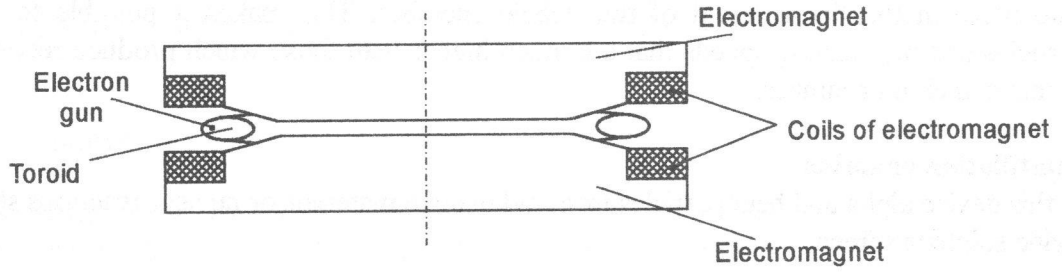


Figure 7-9

The electrons are enclosed in a hollow evacuated toroidal tube. After the electrons have acquired maximum energy they are directed to a metal target. The impact produces high energy x-rays for nuclear studies and for applications in industry and in medicine.

In effect, the betatron is a large x-ray machine, producing energies up to 300 MeV. Beyond this range, electrons rapidly lose energy by electromagnetic radiation.
The coils of the electromagnet are supplied with a.c. current. Thus the electromotive force

$$\oint \mathbf{E}d\mathbf{l} = -\frac{d\Phi}{dt},$$

is induced along the axis of the toroid. If there is an electron moving in a circular path, it experiences an accelerating force

$$F = -eE = \frac{e}{2\pi R}\frac{d\Phi}{dt},$$

where R is the radius of the circular path.

Cyclotron

The cyclotron is a circular accelerator in which various kinds of charged particles could be accelerated. It consists of a large cylindrical box placed between the poles of an electromagnet, producing magnetic field **B**, see Fig. 7-10. The box is exhausted until a very high vacuum exists inside. Charged particles, such as protons or deuterons are fed into the center of the box. Inside the box are two hollow, D-shaped electrodes, called dees, which are connected to the source of high voltage.

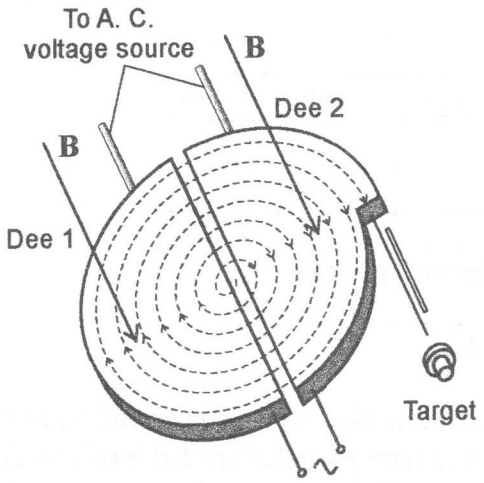


Figure 7-10

When the cyclotron is in operation the polarity of the dees is reversed very rapidly by an oscillator. The combination of an alternating high voltage and the Lorentz force causes the charged particle to take a spiral course. They move faster and faster as they approach the outside of the box having acquired much more energy. When they reach the outer rim of the box they are deflected toward the target.
Supposing that the accelerated particle is a classical one (v<0.87c) we can express the balance of forces acting on the particle as

$$ZevB = \frac{mv^2}{r},$$

where m is the mass of the particle. For a circular path $v = r\omega$. Thus we obtain for maximum velocity of the accelerated particle

$$v_{max} = \frac{2eB}{m}R. \qquad (7\text{-}28)$$

The energy of particle accelerated in a conventional cyclotron may reach 25 MeV. To obtain higher values of energy, it is necessary to modify the accelerator to deal with the increase in mass of the particles as their velocity increases. This increased mass slows down the particles so that they do not reach the gap between the dees when the oscillating voltage reverses. To overcome this difficulty, it is necessary to vary the frequency of the oscillating current. Then, as the mass of the particles increases and their acceleration decreases, the frequency of the oscillator can be reduced. The changes in the voltage of the field are timed to coincide with the slower acceleration of the more massive particles.

This type of accelerator is called a **synchrocyclotron**. It can boost the energy of the particles to about 800 MeV.

Synchrotron

Another type of the particle accelerator is the synchrotron. Like the cyclotron, it operates on the principle of accelerating particles by making them move in a circular path with increasing velocity. However, the path of the particles is confined to a toroid (as in the betatron) by varying both the oscillating voltage and the magnetic field. The energies attainable in a sychrotron are theoretically unlimited, and synchrotrons presently in operation or under operation are extremely powerful. A 25 GeV synchrotron is operated in Geneva, Switzerland, by CERN. High-energy synchrotrons are sometimes called cosmotrons.

Linear accelerators

A linear accelerator is a device that moves charged particles to high energies along a straight path. They are used both individually and in conjunction with other accelerators.

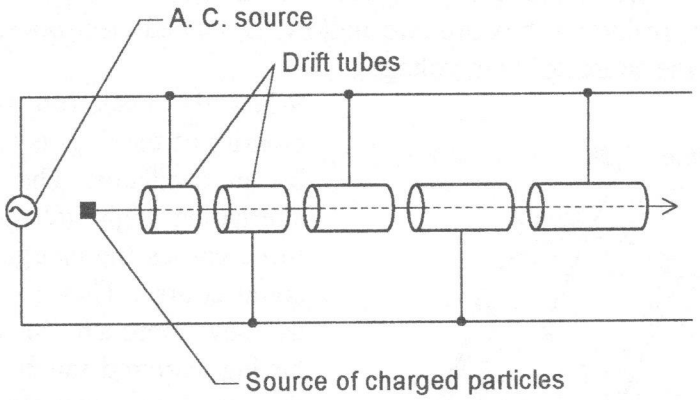


Figure 7-11

A simplified diagram of a linear accelerator is shown in Fig. 7-11. A series of hollow drift tubes is mounted in a long, evacuated chamber. Charged particles are fed into one end of this arrangement and are accelerated by means of a high frequency accelerating voltage applied to the drift tubes. At any given instant alternate tubes have opposite charges. The alternating voltage is timed in such a way that a particle is repelled by the tube it is leaving, and attracted by the tube it is approaching. In this way, the particle is accelerated every time it crosses the gap between two tubes. Because of this acceleration, the drift tubes are successively longer so the particles will always be in a gap when the voltage is reversed.

A Stanford university (USA) operates large linear accelerator, called a collider. This device is devoted to the study of electron-positron collisions. It has been operational since 1987 and the maximum collision energy is 120 MeV. In this collider the electrons are shot at a target to produce positrons. Positrons and electrons are then collected in damping rings. The particles are then accelerated down a 3 km tunnel. At the end of their paths are bent into a head-on collisions course. Finally the energy of collision creates new particles which are recorded in the detector.

7.10 Nuclear Fission

Nuclear fission was discovered by Hahn and Strassman in 1939. They found that the bombardment of uranium by neutrons produces elements in the middle of the periodic table, see Fig. 7-1. It was immediately realized that a very large amount of binding energy would be released in the fission of a nucleus of large Z, into two nuclei of intermediate Z. Nuclear fission is the splitting of a large nucleus into two smaller nuclei. Free neutrons and energy are also released. The fissioning nuclei of a particular isotope will not all split the same way. There are dozens of different ways that a nucleus can split, and there are dozens of different possible fission fragments.

Eq. 7-29 shows a typical fission event, in which ${}^{235}_{92}\mathrm{U}$ absorbs a neutron producing a compound nucleus ${}^{236}_{92}\mathrm{U}$ in a highly excited state. It is this nucleus that undergoes fission, splitting into two fragments. These fragments - between them - rapidly emit two prompt neutrons, leaving ${}^{140}_{54}\mathrm{Xe}$ and ${}^{94}_{38}\mathrm{Sr}$ as fission fragments. Thus

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}\,. \qquad (7\text{-}29) $$

The fragments ${}^{140}_{54}\mathrm{Xe}$ and ${}^{94}_{38}\mathrm{Sr}$ are both highly unstable, undergoing beta decay, until each reaches a stable end product. Thus

$$ {}^{140}_{54}\mathrm{Xe} \rightarrow {}^{140}_{55}\mathrm{Cs} \rightarrow {}^{140}_{56}\mathrm{Ba} \rightarrow {}^{140}_{57}\mathrm{La} \rightarrow {}^{140}_{58}\mathrm{Ce}\,. \qquad (7\text{-}30) $$

The half-life τ of each radionuclide is

14 s 64 s 13 days 40 hours stable.

$$ {}^{94}_{38}\mathrm{Sr} \rightarrow {}^{94}_{39}\mathrm{Y} \rightarrow {}^{94}_{40}\mathrm{Zr}\,, \qquad (7\text{-}31) $$

τ = 75 s 19 min stable.

Measurements soon showed that energy of around 200 MeV per fission was released and carried away largely by the kinetic energy of the two fission fragments. Measurements also showed that two or three neutrons were emitted in each fission. This suggests the possibility of using these neutrons to induce other uranium nuclei to fission, using the neutrons that would be emitted from these fissions in the same way, and so forth, in a **chain reaction**.

There is yet another important aspect that must be taken into account. Almost all of the possible fission fragments are radioactive. These radioactive fragments are important components of the radioactive fallout from nuclear explosions and of the nuclear waste produced in nuclear power plants.

In a nuclear reactor, fission proceeds at a carefully controlled rate. However three difficulties still stand in the way of the working reactor.

1. The neutron leakage problem. Some of the neutrons produced by fission will leak out of the reactor and be lost to the chain reaction. Leakage is a surface effect, its magnitude being proportional to the square of a typical reactor dimension ($6a^2$ for a cube of edge a). Neutron production, however, occurs throughout the volume of the fuel and is thus proportional to the cube of a typical dimension (that is a^3 for a cube). We can make the fraction of neutrons lost by leakage as small as we wish by making the reactor core large enough, thereby reducing the surface to volume ratio (that is $6/a$ for a cube).

2. The neutron energy problem. The neutrons produced by fission are fast, with kinetic energies of about 2 MeV. However, fission is most effectively induced by thermal neutrons. Fat neutrons can be slowed down by mixing the uranium fuel with a substance - called a moderator. The moderator is usually ${}^{12}_{6}C$ in the form of graphite, or ${}^{2}_{1}H$ in the form of deuterium oxide. It is also possible to use water as moderator, the hydrogen nuclei being the effective component.
3. The neutron capture problem. As the fast neutrons generated by fission are slowed down in the moderator to thermal energies (about 0.04 eV), they must pass through a critical energy interval (1-100 eV) in which they are particularly susceptible to non-fission capture by ${}^{238}_{92}U$. Such capture, which results in the emission of a gamma ray, removes the neutron from the fission chain. To minimize such resonance capture, the uranium fuel and the moderator are not intimately mixed but are „clumped" occupying different regions of the reactor volume.

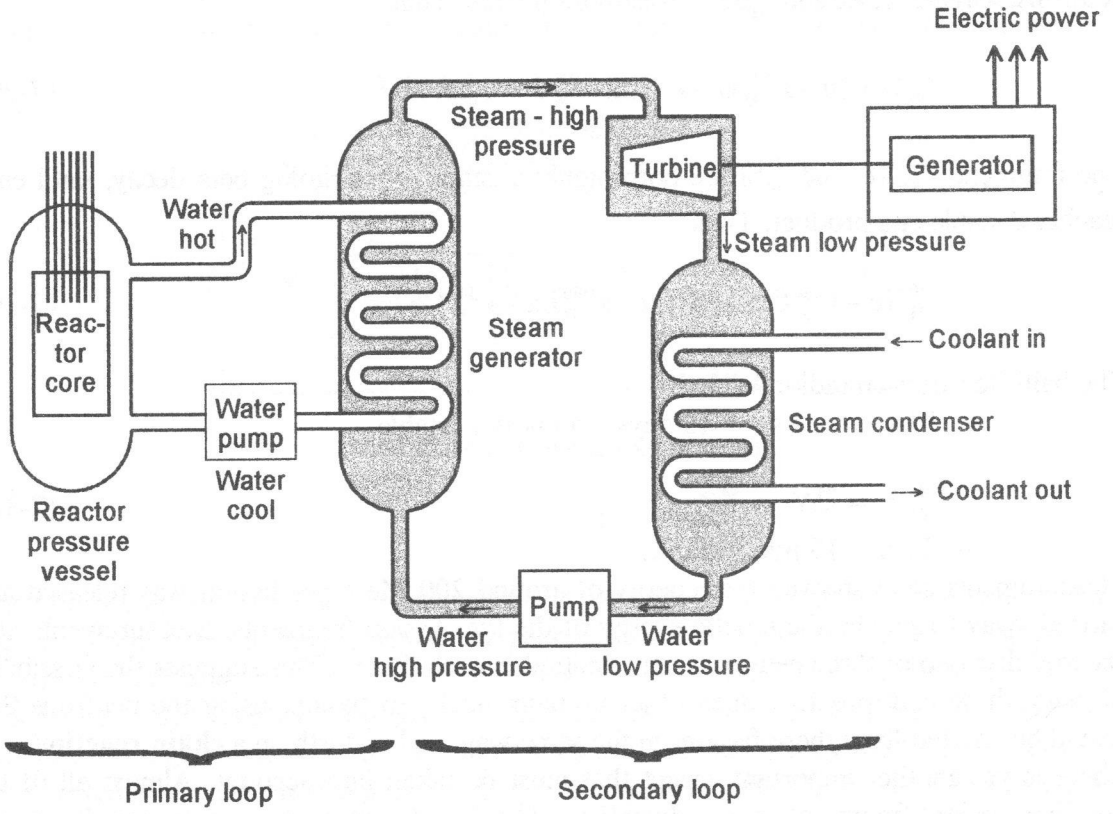


Figure 7-12

A simplified layout of a nuclear reactor, based on a pressurized water reactor is shown in Fig. 7-12. In such a reactor water is used both as a moderator and as a heat transfer medium. In the primary loop, water at high temperature and pressure (600K and 1.5×10^{7} Pa) circulate through the reactor vessel and transfers heat from the reactor core to the steam generator, which provides high-pressure steam to operate the turbine. The turbine then drives the generator. To complete the secondary loop, low-pressure steam from the turbine is condensed to water and forced back into the steam generator by a pump.

To produce an uncontrolled fission reaction, one must ensure that the fission of each nucleus leads to more than one additional fission. This is accomplished by using a high density of fissionable nuclei so that each neutron emitted in fission is likely to encounter

another nucleus. In other words nearly pure uranium 235 or plutonium 239 must be used. However, there must also be a sufficient amount of it, and it must be put into the proper configuration - a sphere for example. The minimum amount of fissionable isotope that is needed is called a critical mass. In Fig. 7-13 we can see the implosion bomb which was dropped on Nagasaki. A subcritical sphere of plutonium 239 is surrounded by a shell of specially shaped conventional explosives. These explosives squeeze the plutonium so much that it becomes a critical mass and explosion occurs.

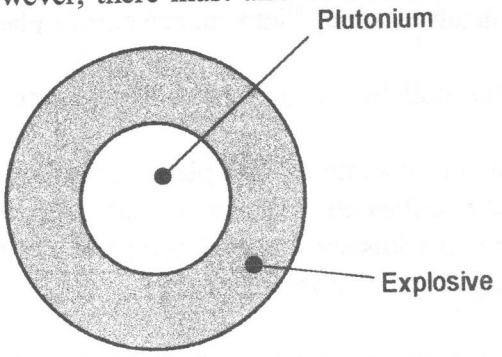


Figure 7-13

7.11 Nuclear Fusion

The binding energy curve of Fig. 7-1 shows that energy is released if two light nuclei combine to form a single large nucleus, a process called nuclear fusion. The process is hindered by the Coulomb repulsion that acts to prevent the two particles from getting close enough to each other to come within range of their attractive nuclear forces and „fusing". The height of the Coulomb barrier depends on the charge and the radii of two interacting nuclei. For more highly-charged particles, the barrier is correspondingly higher. The best way for starting the fusion is to raise the temperature of the matter so that the particles have enough energy - due to their thermal motion alone - to penetrate the barrier. We call this process thermonuclear fusion.
There are many possible fusion reactions that result in a release of energy. Some of these reactions, together with the amount of energy released are:

$$ {}_1^2\mathrm{H} + {}_1^2\mathrm{H} \rightarrow {}_2^3\mathrm{He} + {}_0^1\mathrm{n} + 3.3\ \mathrm{MeV}, \tag{7-32} $$

$$ {}_1^2\mathrm{H} + {}_1^3\mathrm{H} \rightarrow {}_2^4\mathrm{He} + {}_0^1\mathrm{n} + 17.6\ \mathrm{MeV}, \tag{7-33} $$

$$ {}_1^2\mathrm{H} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1\mathrm{p} + 18.3\ \mathrm{MeV}. \tag{7-34} $$

In each case, energy is released because the total mass of the nucleons after the fusion is less than the total mass before. As with fission, the missing mass is converted to energy.
There are no difficulties in obtaining fusion on earth by non-thermal means. It can be done with ease by using a cyclotron, or some other accelerator, to give the bombarding nucleus enough energy to overcome the repulsive Coulomb barrier. However, the amount of energy liberated in the relatively few fusions that can be produced in this way is microscopic compared to the energy that goes into the running the accelerator.
Efficient thermal fusion has, however, been taking place in the stars. For example the fusion reaction in the sun is a multistep process, in which hydrogen is burned into helium, the hydrogen being the fuel, while the helium is the „ashes". This process is called the proton-proton cycle.

There are three requirements for a successful thermonuclear reactor.

1. High particle density n. The density of interacting particles must be great enough to ensure that the deuteron-deuteron collision rate is high enough. At the high temperature required, the deuterium gas will be completely ionized, into quazineutral plasma consisting of deuterons and electrons.
2. A high plasma temperature to ensure that the colliding deuterons will penetrate the Coulomb barrier.
3. A long confinement time τ. A major problem is to contain the hot plasma long enough to ensure that its density and temperature remain sufficiently high for enough of the fuel to be fused. It is clear that no solid container can withstand the high temperatures that are necessary, so confining techniques using magnetic fields are necessary.

It can be shown that for successful operation of a thermonuclear reactor, it is necessary to have

$$n\tau > 10^{20}\ \mathrm{sm}^{-3},$$

a condition known as Lawson's criterion.
Soon after fusion was discovered, scientists looked for ways to harness it as an energy source. Research on controlled fusion is being pursued along a number of avenues. Several of these employ magnetic confinement, specially shaped magnetic fields are used to keep the plasma without letting it to come into contact with the walls of the container. One of the most promising device is called a tokamak - it has plasma confined inside a toroid. Another approach is to use extremely intense bursts of laser light to produce a miniature fusion explosion. A small pellet of solidified fuel is blasted from several directions simultaneously.
There are good reasons why controlled nuclear fusion would make a nice energy source. The principle one is that oceans contain an enormous supply of the fuel-hydrogen nuclei. But because of the technical challenges, controlled fusion seems not be a viable energy source in the nearest time.

PERIODIC TABLE OF THE ELEMENTS

relative mass
element
atomic number

1,079 H 1																	4,00260 He 2
6,941 Li 3	9,0122 Be 4											10,81 B 5	12,011 C 6	14,007 N 7	15,999 O 8	18,998 F 9	20,179 Ne 10
22,990 Na 11	24,305 Mg 12											26,982 Al 13	28,086 Si 14	30,974 P 15	32,06 S 16	35,453 Cl 17	39,948 Ar 18
39,098 K 19	40,08 Ca 20	44,956 Sc 21	47,90 Ti 22	50,941 V 23	51,996 Cr 24	54,938 Mn 25	55,847 Fe 26	58,933 Co 27	58,70 Ni 28	63,546 Cu 29	65,38 Zn 30	69,72 Ga 31	72,56 Ge 32	74,922 As 33	78,96 Se 34	79,904 Br 35	83,80 Kr 36
85,468 Rb 37	87,62 Sr 38	88,906 Y 39	91,22 Zr 40	92,906 Nb 41	95,94 Mo 42	(97) Tc 43	101,07 Ru 44	102,906 Rh 45	106,4 Pd 46	107,868 Ag 47	112,41 Cd 48	114,82 In 49	118,69 Sn 50	121,75 Sb 51	127,60 Te 52	126,905 I 53	131,30 Xe 54
132,905 Cs 55	137,33 Ba 56	*	174,97 Lu 71	178,49 Hf 72	180,948 Ta 73	183,85 W 74	186,207 Re 75	190,2 Os 76	192,22 Ir 77	195,09 Pt 78	196,967 Au 79	200,59 Hg 80	204,37 Tl 81	207,2 Pb 82	208,980 Bi 83	(209) Po 84	(210) At 85	(222) Rn 86
(223) Fr 87	226,025 Ra 88	**	(262) Lr 103	(261) Rf 104	(262) Db 105	(266) Sg 106	(264) Bh 107	(269) Hs 108	(268) Mt 109	(271) Ds 110	(272) Uuu 111	(285) Uub 112		(289) Uuq 114				

* lanthanoids	138,906 La 57	140,12 Ce 58	140,908 Pr 59	144,24 Nd 60	(145) Pm 61	150,4 Sm 62	151,96 Eu 63	157,25 Gd 64	158,925 Tb 65	162,50 Dy 66	164,930 Ho 67	167,26 Er 68	168,934 Tm 69	178,04 Yb 70
** actinoids	227,028 Ac 89	232,038 Th 90	231,036 Pa 91	238,029 U 92	237,048 Np 93	(244) Pu 94	(243) Am 95	(247) Cm 96	(247) Bk 97	(251) Cf 98	(254) Es 99	(257) Fm 100	(258) Md 101	(259) No 102