Fundamentals of Nuclear Physics

Chapters 11-14 from the textbook
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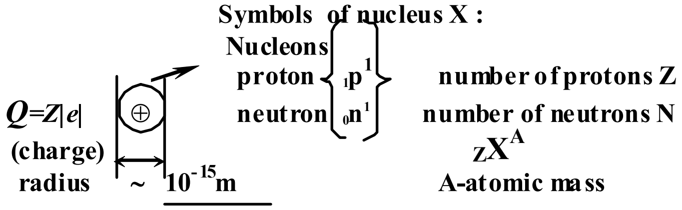
11. Nuclear physics

11.1. Internal structure of an atomic nucleus

All nuclei (besides the ordinary hydrogen nucleus which is a single proton) are composed of two types of particles: protons and neutrons. Some of the properties of nuclei, such as their charge, structure and composition, radius and symbols are shown by the following scheme:



The number of protons in the nucleus equals the **atomic number** Z (and represents the charge of nucleus expressed in elementary charge units). In periodical system, all elements are ordered by their atomic numbers. The number of neutrons in the nucleus $N= A-Z$. Here A is the number of nucleons – the mass number of chemical element X. For example, aluminium $_{13}Al^{27}$ has the mass number 27 and the atomic number 13; therefore, it contains 13 protons and 14 neutrons.

The nuclei of all atoms of a particular element contain the same number of protons, but they may contain different numbers of neutrons. Nuclei that are related in this way are called **isotopes**. **The isotopes of an element have the same Z value, but different N and A values**. The natural abundances of isotopes can differ substantially. Examples are $_{92}U^{235}$ and $_{92}U^{238}$. The natural ore of the uranium consist on about 99.27.9% isotope $_{92}U^{238}$, 0.72 % isotope $_{92}U^{235}$ and 0.01% $_{92}U^{234}$. Some isotopes don't occur naturally, but can be produced in the laboratory through nuclear reactions. Even the simplest element, hydrogen, has isotopes: $_1H^1$, $_1H^2$, $_1H^3$ (hydrogen, deuterium, and tritium).

Proton $\mathbf{_1p^1}$ is the particle with electrical charge $+e$=1,6·10^{-19} C, mass of proton ≈1836m_e. Neutron $\mathbf{_0n^1}$ is electrical neutral particle, $m_n \approx m_p+2{,}5m_e$. Neutron is unstable particle, free neutrons decay in following way

$$_0n^1 \xrightarrow{T_{1/2}=12\,хв} {}_1p^1 + {}_1e^0 + \nu$$

where $\tilde{\nu}$ -special particle, called neutrino(below it will be characterized in detail).

Neutrons are divided in three groups according to their kinetic energy:

thermal (kinetic energy is about kT),
slow (kinetic energy is about one kiloelectron-Volt, keV),
fast (kinetic energy is about MeV).

Experiments have shown that most nuclei are approximately spherical and have an average radius given by formula: r=1,2·10^{-15}A$^{1/3}$ m, where A is the total number of nucleons. Spin of neutron and proton is S=1/2.

Mass-spectrum analysis and nuclear magnetic resonance method are the most important methods of nucleus researches.

11.2. Mass defect and binding energy

The total mass M of a nucleus is always less than the sum of the masses of its nucleons $\Delta m = N \cdot m_n + Z \cdot m_p - M$, here N is total number of neutrons, m_n is mass of neutron , m_p is mass of proton.

Also, because there is an energy associated with any mass, the total energy of the bound system, which is the nucleus, is less than the combined energy of the separated nucleons.

This difference in energy is called the binding energy of the nucleus and can be thought of as the energy that must be added to a nucleus to break it apart into separated neutrons and protons. So $\Delta E = \Delta mc^2$ or

$$\Delta E = c^2[(A-z)m_n + z\cdot m_p - M].$$

Here mass and energy are expressed in kilograms and Joules, respectively.

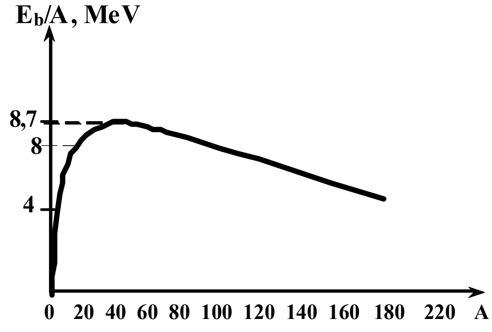


Figure11.1

If the mass is expressed in atomic mass units and energy in MeV, the formula has the form:

$$\Delta E = 931[(A-z)m_n + z\cdot m_p - M].$$

Figure 11.1 shows a graph of the amount of energy required to remove a nucleon from the nucleus. The figure indicates that maximum amount of energy necessary to remove a nucleon is required for nuclei with atomic numbers from 50 to 60. The energy required to remove electron from the atom is million times less than for removing the nucleon from an atomic nucleus. From the figure 11.1 one can see that for light nuclei the binding energy per nucleons increases for atomic mass but it becomes nearly independent on A after reaching its maximum. This is a result of the short-range nature of the nuclear force. A given nucleon interacts only with a few of its nearest neighbours, rather than with all of the nucleons in the nucleus.
Thus, no matter how many nucleons are present in the nucleus, pulling any one nucleon out involves separating it only from its nearest neighbours. The energy to do this, therefore, is approximately independent of how many nucleons are present.

11.3. Nuclear forces. Models of nucleus

11.3.1. Properties of nuclear forces

Nucleus consists of a closely packed collection of protons and neutrons in spite of existence of very large repulsive electrostatic forces between protons ,which should cause the nucleons to fly apart.
Stability of nuclei is caused by presence of another, short–range attractive force, called **nuclear force.**
The characteristics of nuclear forces are the following:
1. Nuclear forces act on very short distance (short-range force).
2. Nuclear forces are charge-independent.
The protons attract each other via the nuclear force, and at the same time they repel each other through the Coulomb force. The attractive nuclear force also acts between pairs of neutrons and between neutrons and protons ($p \rightleftarrows p$, $p \rightleftarrows n$, $n \rightleftarrows p$, $n \rightleftarrows n$). In other words, the nuclear forces associated with proton–proton, proton–neutron, and neutron–neutron interactions are approximately the same, apart from the additional repulsive Coulomb force for the proton–proton interaction.
3. The nuclear attractive force is stronger than the Coulomb repulsive force
If this were not the case, stable nuclei would not exist.
4. Stability of nuclei depends on ratio between protons and neutrons in nuclei.
There are about 260 stable nuclei; hundreds of others have been observed, but are unstable.
5. Nuclei forces are eccentric.
In contrast to electrostatic and gravity forces, which act along the line connecting their centres, nuclear forces are eccentric and depends on orientation of nucleon spins.

11.3.2 Nucleus model

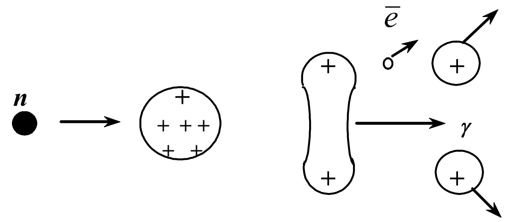


Figure 11.2

One of the simplest models of a nucleus is drop model. This model is useful for qualitative analysis of nuclear fission (figure 11.2). It relies on some similarity between liquid drop and nucleus and is based on the following principles:
1) In both cases (nucleus and liquid drop) the forces to act between particles are short-range;
2) In both cases a little compressibility is observed.

The other popular model, which explains stability of nucleus is shell model. In compliance with this model nucleus consist of shells, filled by protons and neutrons. On every shell only finite number of nucleons can exist. This construction reminds of atom construction. The most stable nuclei are these with 2, 8, 20, 28,40,50, 82,126 nucleons (magic numbers of nucleons) for which the shells are filled. This theory is in accordance with experimental data for binding energy and explains stability of nuclei.

12. Radioactivity

12.1. Radioactive decay

Radioactivity is spontaneous transformation of the nucleus of one element into nucleus of another element which is accompanied by radiation of particles. Three types of radiation can be emitted by a radioactive substance:

alpha (α) particles, in which the emitted particles are nuclei of Helium (^4_2He);

beta (β) particles, in which the emitted particles are either electrons or positrons; and **gamma (γ) rays**, in which the emitted "rays" are high-energy photons. A positron is a particle similar to the electron in all respects, except that it has a positive charge of e^+ (the positron is said to be the antiparticle of the electron.) The symbol e^- is used to designate an electron, and e^+ designates a positron.

Formulas for α and β radiation or α and β radioactive decay (disintegration) of element X to element Y are:

1) ${}_zX^A \rightarrow {}_{z-2}Y^{A-4} + {}_2He^4$ (α-decay);
2) ${}_zX^A \rightarrow {}_{z+1}Y^A + {}_{-1}e^0 + \tilde{\nu}$ (β^--decay);
3) ${}_zX^A \rightarrow {}_{z-1}Y^A + {}_{+1}e^0 + \nu$ (β^+-decay).

Other processes as electron capture, γ- radiation, spontaneous fission of nuclei, proton radioactivity are classified as the radioactive decay processes too.

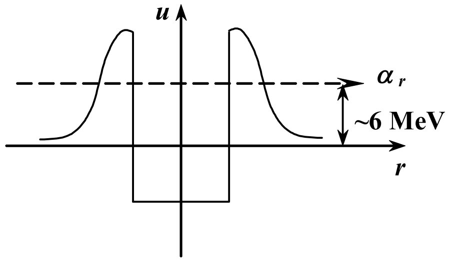


Figure.12.1

The process of α-decay is explained by strong coupling and is accompanied by tunneling effect (Figure 12.1). When α -particle flies out the nucleus it has to get over the energetic barrier higher than it energy.
Only quantum mechanics can explain it by tunneling effect (Figure 12.1), because probability of percolation through the potential barrier of nucleus for α -particle is nonzero

β -decay is explained by another type of coupling, which is called weak coupling. As shown in Figure 12.2,

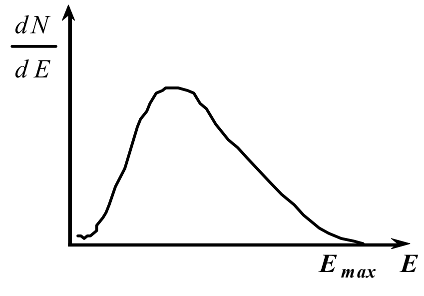


Figure 12.2

only a small number of electrons in β^--decay process have maximum kinetic energy. Most of the emitted electrons have kinetic energies lower than predicted value. If the daughter nucleus and the electron do not carry this liberated energy away, then the question arises: where the energy gone? Analysis of beta decay shows that the principles of conservation of both angular momentum and linear momentum explain this fact. In 1930 Pauli proposed that a third particle must be present to carry away the "missing" energy and to conserve momentum. Later, Enrico Fermi developed a complete theory of beta decay and called this particle the neutrino ν - ("little neutral one") because it had to be electrically neutral and have little or no mass.(look the formula of beta decay). In β^--decay antiparticle to neutrino (antineutrino) is created which is denoted by symbol $\tilde{\nu}$.

The neutrino has the following properties:

1. Zero electric charge.
2. A mass much smaller than that of the electron, but probably not zero (recent experiments suggest that the neutrino definitely has mass, but the value is uncertain– perhaps less than 10^{-37} kg (this estimation is obtained from the analysis of "solar neutrino oscillation" phenomenon).
3. A spin of neutrino S=±1/2
4. Very weak interaction with matter, making it extremely difficult to detect.
5. Antineutrino and neutrino differ one from another only by special characteristic – so called helicity (spirality). This characteristic is determined by correlation between direction of spin and momentum of particle.

12.2. The law of radioactive decay. Gamma rays

Observations have shown that if a radioactive sample contains *N* radioactive nuclei at some instant, then the number of nuclei ΔN, that decay in a small time interval Δt is proportional to *N*. Mathematically, the number of nuclei *dN*, decaying during time *dt* is expressed as:

$$dN = -\lambda N dt ,$$

or

$$\frac{dN}{N} = -\lambda dt .$$

After integration we obtain:

$$\boxed{N = N_0 e^{-\lambda t}}$$ – **The law of radioactive decay,**

here λ is decay constant, N is the number of radioactive nuclei present at time t , N_0 is the number of radioactive nuclei present at time $t = 0$, and e= 2.718 (Euler's constant.)

Radioactivity processes are characterised by activity *A*, which determines the number of decays in unit of time. The unit of activity *A* is the Curie (Ci), defined as 1 Ci=$3{,}7\cdot10^{10}$ decay/s. This unit was selected as the original activity unit because it is the approximate activity of 1 g of radium. The SI unit of activity is the Becquerel (Bq): 1 Bq= 1 decay/s. Therefore, 1 Ci =$3{,}7\cdot10^{10}$ Bq. The most commonly used units of activity are the millicurie (10^{-3} Ci) and the microcurie (10^{-6} Ci).

The half- life time $T_{1/2}$ is the time after a lapse of which, $N_0/2$ radioactive nuclei remain. From the definition of half-life $T_{1/2}$, it follows that: $\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$ and

$$T_{1/2} = \frac{ln 2}{\lambda} .$$

Radioactive nuclei are generally classified into two groups:

1) unstable nuclei found in nature, which give rise to what is called natural radioactivity,

2) nuclei produced in the laboratory through nuclear reactions, which exhibit artificial radioactivity.

Three series of naturally occurring radioactive nuclei (as results of consecutive radioactive decays) exist

$$U^{238} \rightarrow Pb^{206}$$
$$U^{235} \rightarrow Pb^{208}$$
$$Th^{232} \rightarrow Pb^{207}$$

Each starts with a specific long-living radioactive isotope with half-life exceeding that of any of its descendants.

Very often a nucleus that undergoes radioactive decay is left in an excited energy state. The nucleus can then undergo a second decay to a lower energy state by emitting one or more high-energy photons. The photons emitted in the process are called gamma rays, which have very high energy relative to the energy of visible light. The wavelength of gamma rays lies in region 10^{-3} Å - 1 Å (1 Å=$1\cdot10^{-10}$ m).

12.3. Detection of ionizing radiation

Various devices have been developed to detect the energetic particles emitted when a radioactive nucleus decays.

1. The Geiger counter shown in Fig. 12.3 is device used to detect radioactivity and can be considered the prototype of all counters that use the ionization of a medium as the basic detection process.

A Geiger counter consists of a thin wire electrode aligned along the central axis of a cylindrical metallic tube filled with a gas at low pressure. The wire is maintained at a high positive voltage of about 1000 V relative to the tube. When an energetic charged particle or gamma-ray photon enters the tube through a thin window at one end, some of the gas atoms are ionized. The electrons removed from these atoms are attracted toward the wire electrode, and in the process they ionize other atoms in their path. This sequential ionization results in an avalanche of electrons that produces a current pulse. After the pulse has been amplified, it can either be used to trigger an electronic counter or delivered to a loud speaker that clicks each time a particle is detected. **Geiger counter has a deficiency** – it cannot be used to measure the energy of the detected radiation.

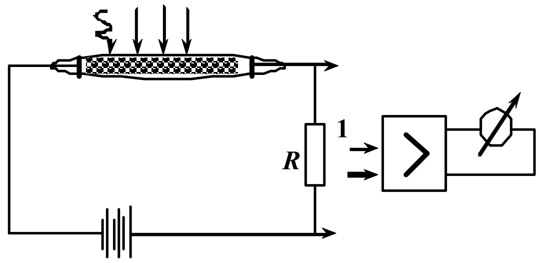


Figure 12.3

2. A semiconductor diode detector is essentially a reverse biased *p–n* junction. As an energetic particle passes through the junction, it produces electron–hole pairs that are separated by the internal electric field. This movement of electrons and holes creates a brief pulse of current that is measured with an electronic counter.

3. A scintillation counter usually uses a solid or liquid material having atoms that are easily excited by radiation. The excited atoms then emit photons of visible light when they return to their ground state. Common materials used as **scintillators are transparent crystals of sodium iodide and certain plastics**. If the scintillator material is attached to one end of a device called a photomultiplier (PM) tube, the photons emitted by the scintillator can be converted to an electrical signal.

Both the scintillator and the semiconductor diode detector are much more sensitive than a Geiger counter, mainly because of the higher mass density of the detecting medium. Both can also be used to measure particle energy from the height of the pulses produced.

4. Track detectors are various devices used to view the tracks or paths of charged particles directly. High-energy particles produced in particle accelerators may have energies ranging from 10^{9} to 10^{12} eV. The energy of such particles can't be measured with the small detectors already mentioned. Instead, their energy and momentum are found from the curvature of their paths in a magnetic field of known magnitude and direction.

4.1 A photographic emulsion is the simplest example of a track detector. A charged particle ionizes the atoms in an emulsion layer. The path of the particle corresponds to a family of points at which chemical changes have occurred in the emulsion. When the emulsion is developed, the particle's track becomes visible.

4.2 A cloud chamber contains a gas that has been supercooled to just below its usual condensation point. An energetic charged particle passing through ionizes the gas along its path. The ions serve as centers for condensation of the supercooled gas. The track can be seen with the naked eye and can be photographed. A magnetic field can be applied to determine the charges of the radioactive particles, as well as their momentum and energy.

4.3 A bubble chamber, invented in 1952 by D. Glaser, uses a liquid (usually liquid hydrogen) maintained near its boiling point. Ions produced by incoming charged particles leave bubble like tracks, which can be photographed. Because the density of the liquid in a bubble chamber is much higher than the density of the gas in a cloud chamber, the bubble chamber has a much higher sensitivity.

4.4. A wire chamber consists of thousands of closely spaced parallel wires that collect the electrons created by a passing ionizing particle. A second grid, with wires perpendicular to the first, allows the x, y position of the particle in the plane of the two sets of wires to be determined. Finally several such x, y grids arranged parallel to each other along the z-axis can be used to determine the particle's track in three dimensions. **Wire chambers form a part of most detectors used at high-energy accelerator labs and provide electronic readouts to a computer for rapid recon.**

12.4. Interaction of ionizing radiation with matter

Radiation absorbed by matter can cause severe damage. The degree and kind of damage depend on several factors, including the type and energy of the radiation and the properties of the absorbing material.

In construction materials the radiation can cause the appearance of different types of structural defects. Radiation damage in biological organisms is due primarily to ionization effects in cells**. The normal function of a cell may be disrupted when highly reactive ions or radicals are formed as the result of ionizing radiation.** Large acute doses of radiation are especially dangerous because damage to a great number of molecules in a cell may cause the cell to die. Also, cells that do survive the radiation may become defective, which can lead to cancer.

In biological systems, it is common to separate radiation damage into two categories: **1) somatic damage** and **2) genetic damage**.

Somatic damage is radiation damage to any cells except the reproductive cells. Such damage can lead to cancer at high radiation levels or seriously alter the characteristics of specific organisms.

Genetic damage affects only reproductive cells. Damage to the genes in reproductive cells can lead to defective offspring. **Clearly, we must be concerned about the effect of diagnostic treatments, such as X-rays and other forms of exposure to radiation**.

Several units are used to quantify radiation exposure and dose.

1. **The roentgen (R)** is defined as that amount of ionizing radiation which will produce $2.08 \cdot 10^9$ ion pairs in 1 cm^3 of air under standard conditions. Equivalently, the roentgen is that amount of radiation which deposits $8.76 \cdot 10^{-3}$ J of energy into 1 kg of air.
2. Unit of absorbed dose in SI is **1 Grey (Gy).** One Grey is that amount of radiation which deposits 1 J of energy into 1 kg of absorbing material.
3. For most applications, the roentgen unit has been replaced by the rad (an acronym for radiation absorbed dose), defined as follows: **One rad** is that amount of radiation which deposits 10^{-2} J of energy into 1 kg of absorbing material.

Although the rad is a perfectly good physical unit, it's not the best unit for measuring the degree of biological damage produced by radiation, because **the degree of damage depends not only on the dose, but also on the type of radiation**.
For example, a given dose of alpha particles causes about 10 times more biological damage than an equal dose of x-rays. The RBE (relative biological effectiveness) factor is defined as the number of rads of x-radiation or gamma radiation that produces the same biological damage as 1 rad of the radiation being used. The RBE factors for different types of radiation are given in Table 12.1.

Type of radiation	**RBE**
γ and X-rays	1.0
β-particles	1.0-1.7
Slow neutrons	4.0-5.0
α-particles	10-20
Fast neutrons and protons	10.0
Heavy ions	20.0

12.5. Biological effects of ionising radiation

The negatively charged electrons and positively charged ions created by ionizing radiation may cause damage in living tissue. If the dose is sufficient, the effect may be seen almost immediately, in the form of radiation poisoning. Lower doses may cause cancer or other long-term problems. Alpha and beta rays cause most damage when they are emitted inside the human body. Gamma rays are less ionizing than either alpha or beta rays, but protection against them requires thicker shielding. They produce damage similar to that caused by X-rays such as burns, and cancer through mutations in the DNA. Natural radioactivity is inherent to atmospheric air, causes of which are cosmic rays and presence of radon in the air. Radon-222 is produced by the decay of Rn-226 which is present wherever uranium is. Since radon is a gas, it seeps out of uranium-containing soils found across most of the world and may concentrate in well-sealed homes. Humans and animals can also be exposed to ionizing radiation internally: if radioactive isotopes are present in the environment, they may be taken into the body. For example, radioactive iodine is treated as normal iodine by the body and used by the thyroid; its accumulation there often leads to thyroid cancer. Although exposure to ionizing radiation carries a risk, it is impossible to completely avoid exposure. Radiation has always been present in the environment and in our bodies. We can, however, avoid undue exposure. In addition, there are some factors able to reduce risk, namely exposition time, distance to the radiation source and proper shielding. For people who are exposed to radiation in addition to natural background radiation, limiting or minimizing the exposure time will reduce the dose from the radiation source. The intensity of the radiation decreases with distance from the source of the radiation. The dose decreases dramatically at increase of distance from the source. Alpha radiation consists of heavy helium-4 nuclei and is readily stopped by a sheet of paper. Beta radiation, consisting of electrons, is halted by an aluminium plate. Gamma radiation is eventually absorbed as it penetrates a dense material. Barriers of lead, concrete, or water give good protection from penetrating radiation such as gamma rays and neutrons. This is why certain radioactive materials are stored or handled underwater or by remote control in rooms constructed of thick concrete or lined with lead. Inserting the proper shield between human body and the radiation source greatly reduces or eliminate the extra radiation dose.

13. Nuclear transformations
13.1 Nuclear reactions

The processes of interaction between nucleus X and elementary particle Y or between two nuclei as result of which the structure of nuclei is changed are called **nuclear reactions**.

Examples of nuclear reactions:

$$\text{Fission reactions} \rightarrow \begin{cases} {}_{92}U^{235} + {}_0n^1 \rightarrow Rb^{140} + Cs^{92} + 2 \div 3_0 n^1 \\ {}_{92}U^{238} + {}_0n^1 \rightarrow {}_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + \beta^- \end{cases}$$

$$\text{Fusion reactions} \rightarrow \begin{cases} {}_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + {}_0n^1 \\ {}_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1p^1 \end{cases}$$

Nuclear reactions are characterized by probability, numerically represented as capture cross section of elementary particle by nucleus of target σ (Figure13.1)

$$\sigma = \frac{1}{nx} ln \frac{N_0}{N},$$

here n is concentration of nuclei, x is depth of target, N_0 is number of particles on the surface of target, N is number of particles on the depth x of the target. Typical order of magnitude for capture cross section is σ~10^{-24} cm^2. At increasing kinetic energy of bombarding particles the probability of their capture by the target nuclei decreases as seen from fig. 13.1 (b). For some value of energy E, sharp peak is observed, which corresponds to so-called resonant absorption. For practical reasons in nuclear reactors neutrons should be slowed down to increase the probability of reaction.

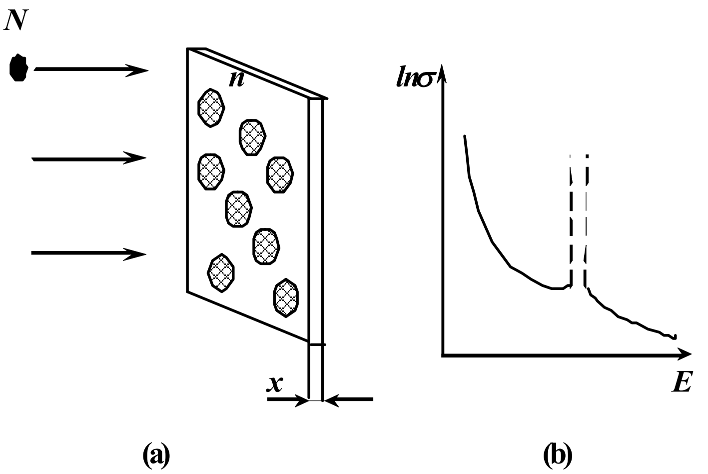


Figure13.1

The first fusion reaction was accomplished by radiation of nuclei ${}_7N^{14}$ with alpha particles in 1919 by Ernest Rutherford. A nuclear fission was accomplished in 1938. The investigations demonstrated different possible ways of fission.

A nuclear fission event is described by the liquid-drop model of the nucleus (Figure13.2).

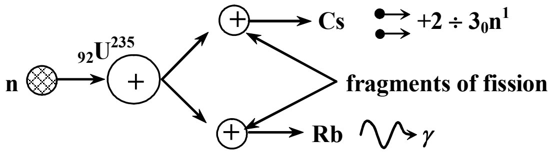


Figure 13.2

The process results in the production of several (typically two or three) neutrons per fission event at first. Electrons, gamma-rays can appear besides neutrons as result of reaction too. In the fission of uranium, about 90 different daughter nuclei can be formed.

Let us dwell on some details of nuclear fission, described by above formula and shown on figure13.2.

1) Neutron approaches a U^{235} nucleus.

2)The neutron is absorbed by the U^{235} nucleus, changing it to U^{236}, which is a U^{236} nucleus in an excited state.

3) The nucleus deforms like a liquid drop.

4) The nucleus undergoes fission, resulting in two lighter nuclei X and Y (Cs and Rb), along with several neutrons.

The energy released in a typical fission process *Q* can be estimated. The binding energy per nucleon is about 7.2 MeV for heavy nuclei (those having a mass number of approximately 240) and about 8.2 MeV for nuclei of intermediate mass. This means that the nucleons in the fission fragments are more tightly bound, and therefore have less mass, than the nucleons in the original heavy nucleus. The decrease in mass per nucleon appears as released energy when fission occurs. The amount of energy released is (8.2 -7.2) MeV per nucleon. Assuming a total of 240 nucleons, we find that the energy released per fission event is *Q*=240 nucleons/(8.2 MeV/nucleon -7.2 MeV/nucleon) -240 MeV

This is a large amount of energy relative to the amount released in chemical processes. For example, the energy released in the combustion of one molecule of the octane used in gasoline engines is about one hundred-millionth the energy released in a single fission event .

13.2 Nuclear reactor

A nuclear reactor is a system designed to maintain a selfsustained chain reaction

1. Most reactors in operation today also use uranium as fuel. Natural uranium contains only about 0.7% of the U^{235} isotope, with the remaining 99.3% being the U^{238} isotope. This is important to the operation of a reactor because fission of U^{238} is much less probable. Instead, it tends to absorb neutrons, producing neptunium and plutonium. For this reason reactor fuels must be artificially enriched so that they contain several percent of the U^{235}. In order to achieve a self-sustained chain reaction, one of the neutrons must be captured by another U^{235} nucleus and cause it to undergo fission.

A useful parameter for describing the level of reactor operation is the reproduction coefficient *K*, defined the average number of neutrons from each fission event N_n that will cause neutrons of another event N_{n+1}: $K = \frac{N_{n+1}}{N_n}$. **A self-sustained chain reaction is achieved when coefficient *K* =1**. Under this condition, the reactor is said to be critical. When $K<1$, the reactor is subcritical and the reaction dies out. When $K>1$, the reactor is said to be supercritical, and a runaway reaction occurs.

An average of about 2.5 neutrons are emitted in each fission event of U^{235}. But if the mass of piece less than certain critical, majority of emitted neutrons fly outward and reaction is stopped.

The basic design of a nuclear reactor is shown in Figure 13.3.

1. The fuel elements consist of enriched uranium.

2. In order for the chain reaction to continue, the neutrons must be slowed down. This is accomplished by surrounding the fuel with a substance called a moderator.

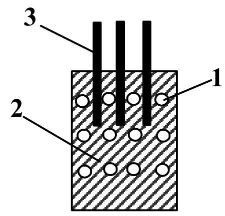


Figure13.3

Carbon nuclei are about 12 times more massive than neutrons, but after about 100 collisions with carbon nuclei, a neutron is slowed sufficiently to increase its likelihood of fission with U^{235}. In some designs of nuclear reactor the carbon is used as the moderator; other reactors use heavy water (D_2O) as the moderator, because neutron is slowed sufficiently after 25 collisions in this case. Some experimental reactor designs uses beryllium as moderator.

3. To control the power level, control rods are inserted into the reactor core. These rods are made of materials such as cadmium that are highly efficient in absorbing neutrons. By adjusting the number and position of the control rods in the reactor core, the *K* value can be varied and any power level within the design range of the reactor can be achieved.

4. In any reactor, a fraction of the neutrons produced in fission will leak out of the core before inducing other fission events. If the fraction leaking out is too large, the reactor will not operate.

The percentage lost is large if the reactor is very small because leakage is a function of the ratio of surface area to volume. Therefore, a critical requirement of reactor design is choosing the correct surface-area-to-volume ratio so that a sustained reaction can be achieved.
The simplified diagram of pressurized water nuclear reactor is shown in figure 13.4.

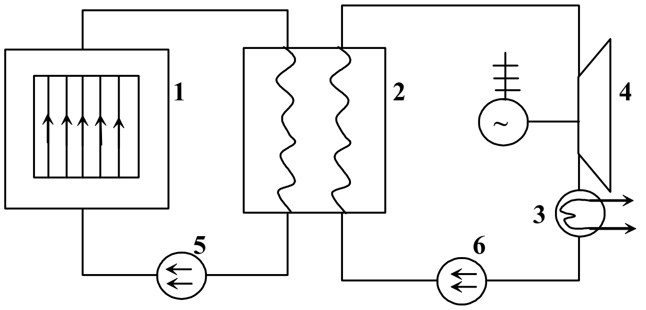


Figure 13.4

Fission events in the reactor core supply heat to the water contained in the primary (closed) system, which is maintained at high pressure to keep it from boiling. This water also serves as the moderator. The hot water is pumped through a heat exchanger, and the heat is transferred to the water contained in the secondary system. There the hot water is converted to steam, which drives a turbine–generator to create electric power. Note that the water in the secondary system is isolated from the water in the primary system in order to prevent contamination of the secondary water and steam by radioactive nuclei from the reactor core.

14. Modern views on the Universe structure. Course conclusions

Modern physics began near the end of 19century. Modern physics developed mainly because of the discovery that many physical phenomena could not be explained by classical physics. The two most important developments in this modern era were the Einstein's theory of relativity and quantum mechanics. Einstein's theory of relativity completely revolutionized the concepts of space, time and energy and is the first step to understand the Universe. Quantum mechanics was formulated by a number of famous scientists to provide descriptions of physical phenomena at the atomic and nuclear level.

Perhaps the key to understanding the early Universe is first to understand the world of elementary particles. Cosmologists and particle physicists find that they have many common goals and are joining efforts to study the physical world at its most fundamental level. This part is devoted to principles of Einstein theory, fundamental forces, modern classification of particles and most profound principles of Nature.

Problem 1

Calculate reduction of mass Δm, corresponding to the energy, produced by power plant with power $P = 2.5\cdot 10^3$ MW during one hour.

Strategy. Recollect formulas**: 1-** Mass defect and binding energy; 2- Energy and power.

Solution

$$1)\ \Delta E = \Delta m c^2;\ 2)\ \Delta E = Pt;\ \ 3)\ \Delta m = \frac{Pt}{c^2},$$

$$\Delta m = \frac{2.5\cdot 10^9\cdot 3600}{9\cdot 10^{16}} = 1\cdot 10^{-4}\,\text{kg}$$

Problem 2.

Calculate the energy, liberated as result of nucleus reaction $_3Li^7 + _1H^1 \to 2_3He^4$, if in present reaction 0.25 grams of helium is created. Helium nuclei atomic mass m_1=4.00387 a.m.u. Lithium nuclei atomic mass m_2=7.01824 a.m.u. Atomic mass of proton m_3=1.00759 a.m.u.

Strategy. Use the formula of energy , liberated as result of nucleus reaction $\Delta E = \Delta mc^2$. In this case mass defect is equal to the difference between sum of particles' mass before reaction and after reaction.

Solution

1) $\Delta M = \Sigma M_I - \Sigma M_{II}$ =7.01824 + 1.00759 - 2·4.00387 =8.02583 – 8.00774 = 0.01809 a.m.u.;

2) In MeV the energy of nuclear reaction is expressed by formula: $\Delta E = 931\Delta M$ = 16.76 MeV.

Problem 3.

Initial mass of radioactive Co is m_0=4 g. Find the mass of Co decayed during 216 day, if its half life $T_{1/2}$ =72 days.

Strategy.

At first find initial number of nuclei. Then apply the law of radioactive decay.

1) $N_0 = \frac{m_0}{\mu}$; (here μ is atomic mass of Co)

2) $N = N_0 e^{-\lambda t}$ (law of radioactive decay)

3) $\lambda = \frac{ln 2}{T_{1/2}}$ (connection between decay constant λ and **half life**

4) $m = \mu N$;

5) $m = m_0 e^{-\lambda t}$ (From steps 1 and 2).

Then find mass of cobalt present after 72 day.

6) $m = 4 \cdot 10^{-3} \cdot e^{-\frac{ln 2}{72} \cdot 216} = 4 \cdot 10^{-3} \cdot 2^{-3} = 0.5 \cdot 10^{-3}$ kg.

7) **Mass of decayed Co** m_{dec}= $4 \cdot 10^{-3} - 0.5 \cdot 10^{-3} = 3.5 \cdot 10^{-3}$ kg.

14.1 The principles of Einstein's theory of relativity

Newtonian mechanics was formulated to describe the motion of objects, and its formalism is quite successful in describing a wide range of phenomena that occur at low speeds. It fails, however, when applied to particles having speeds approaching that of light.

Einstein suggested that space and time must be stretched and compressed as seen by observers in different frames of reference. Since velocity equals distance divided by time, an appropriate distortion of time and space causes the speed of light to be the same in all frames of reference.

Einstein theory is based on two principles

1**. The principle of relativity**:

All the laws of physics are the same in all inertial frames.

2**. The constancy of the speed of light**:

The speed of light in a vacuum has the same value, c =2.997 924 58 $\cdot 10^8$ m/s, in all inertial reference frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

The existence of a universal speed limit means that obvious consequences include the fact that observers moving at different speeds will measure different time intervals and displacements between the same two events length, time, and simultaneity, which are quite different in relativistic mechanics from what they are in Newtonian mechanics.

In relativistic mechanics, there is no such thing as absolute length or absolute time.

As examples that besides its well-known and essential role in theoretical physics, the special theory of relativity has practical applications in nuclear power plants, navigation and global positioning system (GPS) units. All these applications work due to relativistic principles.

14.2. The fundamental forces of Nature

There are four fundamental forces of nature:

1. the strong (hadronic);
2. electromagnetic;
3. weak;
4. gravitational forces.

The strong force is the force between nucleons that keeps the nucleus together. The weak force is responsible for beta decay. The electromagnetic and weak forces are now considered to be manifestations of a single force called the **electroweak force**.

Every fundamental interaction is said to be mediated by the exchange of field particles. The strong force, mediated by gluons, holds quarks (both type are called fundamental particles) together to form composite particles such as protons, neutrons, and mesons. The electromagnetic interaction is mediated by the photon, the weak interaction by the W and Z^0 bosons, the gravitational interaction by gravitons, and the strong interaction by gluons. A major question is why the photon has no mass while the W and Z bosons do. Because of this mass difference, the electromagnetic and weak forces are quite distinct at low energies, but become similar in nature at very high energies, where the rest energies of the W and Z bosons are insignificant fractions of their total energies. This behavior during the transition from high to low energies, called symmetry breaking, does not answer the question of the origin of particle masses. To resolve that problem, a hypothetical particle called the Higgs boson has been proposed which provides a mechanism for breaking the electroweak symmetry and bestowing different particle masses on different particle

European organization for nuclear research (CERN) has started the Large Hadron Collider (LHC), a proton–proton collider that will provide a center-of-mass energy of 14 TeV and allow an exploration of Higgs-boson physics.

The accelerator is constructed in the 27-km circumference tunnel. In such a device, particles with equal masses and kinetic energies, travelling in opposite directions in an accelerator ring, collide head-on to produce the required reaction and the formation of new particles.

14.3. Modern classification of particles. Quarks

In microcosm the particles are classified into elementary particles, which are not molecules, atoms or nuclei (besides proton). At present about 400 elementary particles are known.

Particles can be classified into two broad categories, according to the interactions they take part in:

1. hadrons
2. leptons.

Hadrons interact through the strong force. There are two classes of hadrons, namely mesons and baryons, distinguished by their masses and spins. Baryons have masses equal to or greater than the proton mass (the name baryon means "heavy" in Greek), and their spin is always a non-integer value (1/2 or 3/2). Protons and neutrons are baryons, as are many other particles. **Recent theories postulate that all hadrons are composed of smaller units known as quarks** which have fractional electric charges and baryon numbers of 1/3 and come in six "flavors": up, down, strange, charmed, top, and bottom. Each baryon contains three quarks, and each meson contains one quark and one antiquark. According to the theory of quantum chromodynamics, quarks have a property called color, and the strong force between quarks is referred to as the color force. The color force increases as the distance between particles increases, so quarks are confined and are never observed in isolation.

When two bound quarks are widely separated, a new quark–antiquark pair forms between them, and the single particle breaks.

Leptons have no known structure, down to the limits of current resolution (about 10^{-19} m).

They are called fundamental particles. Leptons interact only through the weak and electromagnetic forces. There are six leptons: the electron (e^-), the muon (μ^-) the tau (τ^-); and their associated neutrinos, ν_e, ν_μ and ν_τ.

14.4. The Big Bang theory of the creation of the Universe

Modern theory of the creation of the Universe, known as the Big Bang theory, states that the Universe had a beginning 13.7 billion years ago. In the moment of Big Bang all matter ant the space-time itself has been created. The first few minutes after the Big Bang the early Universe has extremely high energy density and it is believed that all four interactions of physics were unified and all matter was contained in an undifferentiated "quark soup." The evolution of the four fundamental forces from the Big Bang to the present consists of some important intervals.

1. During the first 10^{-43} s (the **ultrahot epoch, with temperature T=10^{32}K**), it is presumed that the strong, electroweak, and gravitational forces were joined to form a completely unified force.

2. In the first 10^{-35} s following the Big Bang (the **hot epoch, with T=10^{29} K**), gravity broke free of this unification and the strong and electroweak forces remained as one, described by a grand unification theory. This was a period when particle energies were so great (10^{16} GeV) that very massive particles as well as quarks, leptons, and their antiparticles, existed.

3. Then, after 10^{-35} s, the Universe rapidly expanded and cooled (the warm epoch, T in range from 10^{29} K to 10^{15} K), the strong and electroweak forces parted company, and the grand unification scheme was broken. As the Universe continued to cool, the electroweak force split into the weak force and the electromagnetic force about 10^{-10} s after the Big Bang.

4. After a few minutes, protons condensed out of the hot soup.

5. For half an hour the Universe underwent thermonuclear detonation, exploding like a hydrogen bomb and producing most of the helium nuclei now present.

6. The Universe continued to expand, and its temperature dropped. Until about 700000 years after the Big Bang, the Universe was dominated by radiation. Energetic radiation prevented matter from forming single hydrogen atoms because collisions would instantly ionize any atoms that might form. Photons underwent continuous Compton scattering from the vast number of free electrons, resulting in a Universe that was opaque to radiation.

7. By the time the Universe was about 700000 years old, it had expanded and cooled to about 3000 K, and protons could bind to electrons to form neutral hydrogen atoms. The energies of the atoms are quantized, and short-wavelength radiation were not absorbed by atoms anymore. The Universe suddenly became transparent to photons. Radiation no longer dominated the Universe, and clumps of neutral matter grew steadily—first atoms, followed by molecules, gas clouds, stars, and finally galaxies.

The four forces became distinguishable during the first microsecond. Following this, all the quarks combined to form particles that interact via the strong force. The leptons remained separate, however, and exist as individually observable particles to this day.

14.5. The problems of modern physics. Conclusions

Observation of the events that occur when two particles collide in an accelerator is essential in reconstructing the early moments in cosmic history. Perhaps the key to understanding the early Universe is first to understand the world of elementary particles. Cosmologists and particle physicists find that they have many common goals and are joining efforts to study the physical world at its most fundamental level.

Our understanding of physics at short and long distances is far from complete.

1. Why is there so little antimatter in the known Universe?
2. Do neutrinos contribute to the “dark matter” holding the Universe together gravitationally?
3. How can we understand the latest astronomical measurements, which show that the expansion of the Universe is accelerating and that there may be a kind of “antigravity force” acting between widely separated galaxies?
4. Is it possible to unify the strong and electroweak theories in a logical and consistent manner?
5. Why do quarks and leptons form three similar but distinct families?
6. Why are some particles charged and others neutral?
7. Why do quarks carry a fractional charge?
8. What determines the masses of the fundamental particles?
9. An important question that remains is whether leptons and quarks have a substructure. If they do, one could envision an infinite number of deeper structure levels. However, if leptons and quarks are indeed the ultimate constituents of matter, as physicists today tend to believe, we should be able to construct a final theory of the structure of matter, as Einstein dreamed of doing.

The questions go on and on. Because of the rapid advances and new discoveries in the related fields of particle physics and cosmology, by the time you read this book some of these questions may have been resolved and others may have emerged.

The most successful new theory of Universe is superstring theory. In accordance with this theory everything in Universe is constructed of very short nine-dimensional particles, or strings, moving forward in time, the tenth dimension.

In the view of many physicists, the end of the road is in sight, but how long it will take to reach that goal is anyone’s guess.