Chapter 1

Inside atomic nucleus

Amazingly enough, human mind that is kind of contained inside a couple of liters of human's brain, is able to deal with extremely large as well as extremely small objects such as the whole universe and its smallest building blocks. So, what are these building blocks? As we already know, the universe consists of galaxies, which consist of stars with planets moving around. The planets are made of molecules, which are bound groups (chemical compounds) of atoms.

There are more than 10^{20} stars in the universe. Currently, scientists know over 12 million chemical compounds i.e. 12 million different molecules. All this variety of molecules is made of only a hundred of different atoms. For those who believe in beauty and harmony of nature, this number is still too large. They would expect to have just few different things from which all other substances are made. In this chapter, we are going to find out what these elementary things are.

1.1 What the atom is made of

The Greek word $\alpha\tau o\mu o\nu$ (atom) means indivisible. The discovery of the fact that an atom is actually a complex system and can be broken in pieces was the most important step and pivoting point in the development of modern physics.

It was discovered (by Rutherford in 1911) that an atom consists of a positively charged nucleus and negative electrons moving around it. At first, people tried to visualize an atom as a microscopic analog of our solar system where planets move around the sun. This naive planetary model assumes that in the world of very small objects the Newton laws of classical mechanics are valid. This, however, is not the case.

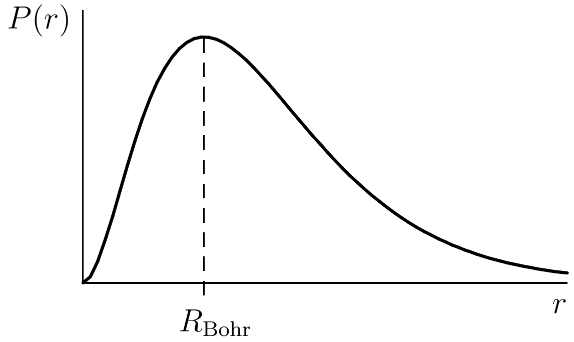


Figure 1.1: Probability density $P(r)$ for finding the electron at a distance r from the proton in the ground state of hydrogen atom.

The microscopic world is governed by quantum mechanics which does not have such notion as trajectory. Instead, it describes the dynamics of particles in terms of quantum states that are characterized by probability distributions of various observable quantities.

For example, an electron in the atom is not moving along a certain trajectory but rather along all imaginable trajectories with different probabilities. If we were trying to catch this electron, after many such attempts we would discover that the electron can be found anywere around the nucleus, even very close to and very far from it. However, the probabilities of finding the electron at different distances from the nucleus would be different. What is amazing: the most probable distance corresponds to the classical trajectory!

You can visualize the electron inside an atom as moving around the nucleus chaotically and extremely fast so that for our “mental eyes” it forms a cloud. In some places this cloud is more dense while in other places more thin. The density of the cloud corresponds to the probability of finding the electron in a particular place. Space distribution of this density (probability) is what we can calculate using quantum mechanics. Results of such calculation for hydrogen atom are shown in Fig. 1.1. As was mentioned above, the most probable distance (maximum of the curve) coincides with the Bohr radius.

Quantum mechanical equation for any bound system (like an atom) can have solutions only at a discrete set of energies $E_1, E_2, E_3 \ldots$, etc. There are simply no solutions for the energies E in between these values, such as, for instance, $E_1 < E < E_2$. This is why a bound system of microscopic particles cannot have an arbitrary energy and can only be in one of the quantum states. Each of such states has certain energy and certain space configuration, i.e. distribution of the probability.

A bound quantum system can make transitions from one quantum state to another either spontaneously or as a result of interaction with other systems. The energy conservation law is one of the most fundamental and is valid in quantum world as well as in classical world. This means that any transition between the states with energies E_i and E_j is accompanied with either emission or absorption of the energy $\Delta E = |E_i - E_j|$. This is how an atom emits light.

Electron is a very light particle. Its mass is negligible as compared to the total mass of the atom. For example, in the lightest of all atoms, hydrogen, the electron constitutes only 0.054% of the atomic mass. In the silicon atoms that are the main component of the rocks around us, all 14 electrons make up only 0.027% of the mass. Thus, when holding a heavy rock in your hand, you actually feel the collective weight of all the nuclei that are inside it.

1.2 Nucleus

Is the nucleus a solid body? Is it an elementary building block of nature? No and no! Although it is very small, a nucleus consists of something even smaller.

1.2.1 Proton

The only way to do experiments with such small objects as atoms and nuclei, is to collide them with each other and watch what happens. Perhaps you think that this is a barbaric way, like colliding a "Mercedes" and "Toyota" in order to learn what is under their bonnets. But with microscopic particles nothing else can be done.

In the early 1920's Rutherford and other physicists made many experiments, changing one element into another by striking them with energetic helium nuclei. They noticed that all the time hydrogen nuclei were emitted in the process. It was apparent that the hydrogen nucleus played a fundamental role in nuclear structure and was a constituent part of all other nuclei. By the late 1920's physicists were regularly referring to hydrogen nucleus as *proton*. The term "proton" seems to have been coined by Rutherford, and first appears in print in 1920.

1.2.2 Neutron

Thus it was established that atomic nuclei consist of protons. Number of protons in a nucleus is such that makes up its positive charge. This number, therefore, coincides with the atomic number of the element in the Mendeleev's Periodic table.

This sounded nice and logical, but serious questions remained. Indeed, how can positively charged protons stay together in a nucleus? Repelling each other by electric force, they should fly away in different directions. Who keeps them together?

Furthermore, the proton mass is not enough to account for the nuclear masses. For example, if the protons were the only particles in the nucleus, then a helium nucleus (atomic number 2) would have two protons and therefore only twice the mass of hydrogen. However, it actually is four times heavier than hydrogen. This suggests that it must be something else inside nuclei in addition to protons.

These additional particles that kind of "glue" the protons and make up the nuclear mass, apparently, are electrically neutral. They were therefore called *neutrons*. Rutherford predicted the existence of the neutron in 1920. Twelve years later, in 1932, his assistant James Chadwick found it and measured its mass, which turned out to be almost the same but slightly larger than that of the proton.

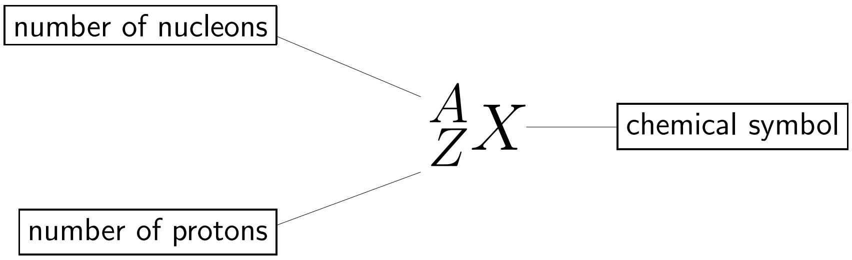
1.2.3 Isotopes

Thus, in the early 1930's it was finally proved that atomic nucleus consists of two types of particles, the protons and neutrons. The protons are positively charged while the neutrons are electrically neutral. The proton charge is exactly equal but opposite to that of the electron. The masses of proton and neutron are almost the same, approximately 1836 and 1839 electron masses, respectively.

Apart from the electric charge, the proton and neutron have almost the same properties. This is why there is a common name for them: *nucleon*. Both the proton and neutron are nucleons, like a man and a woman are both humans. In physics literature, the proton is denoted by letter p and the neutron by n. Sometimes, when the difference between them is unimportant, it is used the letter N meaning nucleon (in the same sense as using the word "person" instead of man or woman).

Chemical properties of an element are determined by the charge of its atomic nucleus, i.e. by the number of protons. This number is called the *atomic number* and is denoted by letter Z. The mass of an atom depends on how many nucleons its nucleus contains. The number of nucleons, i.e. total number of protons and neutrons, is called the *atomic mass number* and is denoted by letter A.

Standard nuclear notation shows the chemical symbol, the mass number and the atomic number of the isotope.



For example, the iron nucleus (26-th place in the Mendeleev's periodic table of the elements) with 26 protons and 30 neutrons is denoted as

$$^{56}_{26}\mathrm{Fe}\ ,$$

where the total nuclear charge is $Z = 26$ and the mass number $A = 56$. The number of neutrons is simply the difference $N = A - Z$ (here, it is used the same letter N, as for nucleon, but this should not cause any confusion). Chemical symbol is inseparably linked with Z. This is why the lower index is sometimes omitted and you may encounter the simplified notation like $^{56}\mathrm{Fe}$.

If we add or remove a few neutrons from a nucleus, the chemical properties of the atom remain the same because its charge is the same. This means that such atom should remain in the same place of the Periodic table. In Greek, "same place" reads *ίσος τόπος* (isos topos). The nuclei, having the same number of protons, but different number of neutrons, are called therefore *isotopes*.

Different isotopes of a given element have the same atomic number Z, but different mass numbers A since they have different numbers of neutrons N. Chemical properties of different isotopes of an element are identical, but they will often have great differences in nuclear stability. For stable isotopes of the light elements, the number of neutrons will be almost equal to the number of protons, but for heavier elements, the number of neutrons is always greater than Z and the neutron excess tends to grow when Z increases. This is because neutrons are kind of glue that keeps repelling protons together. The greater the repelling charge, the more glue you need.

1.3 Nuclear force

Since atomic nuclei are very stable, the protons and neutrons must be kept inside them by some force and this force must be rather strong. What is this force? All of modern particle physics was discovered in the effort to understand this force!

Trying to answer this question, at the beginning of the XX-th century, physicists found that all they knew before, was inadequate. Actually, by that time they knew only gravitational and electromagnetic forces. It was clear that the forces holding nucleons were not electromagnetic. Indeed, the protons, being positively charged, repel each other and all nuclei would decay in a split of a second if some other forces would not hold them together. On the other hand, it was also clear that they were not gravitational, which would be too weak for the task.

The simple conclusion was that nucleons are able to attract each other by yet unknown *nuclear forces*, which are stronger than the electromagnetic ones. Further studies proved that this hypothesis was correct.

Nuclear force has rather unusual properties. Firstly, it is charge independent. This means that in all pairs nn, pp, and np nuclear forces are the same. Secondly, at distances $\sim 10^{-13}$ cm, the nuclear force is attractive and very strong, ~ 100 times stronger than the electromagnetic repulsion. Thirdly, the nuclear force is of a very short range. If the nucleons move away from each other for more than few *fermi*

(1 fm=10^{-13} cm) the nuclear attraction practically disappears. Therefore the nuclear force looks like a "strong man with very short hands".

1.4 Binding energy and nuclear masses

1.4.1 Binding energy

When a system of particles is bound, you have to spend certain energy to disintegrate it, i.e. to separate the particles. The easiest way to do it is to strike the system with a moving particle that carries kinetic energy, like we can destroy a glass bottle with a bullet or a stone. If our bullet-particle moves too slow (i.e. does not have enough kinetic energy) it cannot disintegrate the system. On the other hand, if its kinetic energy is too high, the system is not only disintegrated but the separated particles acquire some kinetic energy, i.e. move away with some speed. There is an intermediate value of the energy which is just enough to destroy the system without giving its fragments any speed. This minimal energy needed to break up a bound system is called *binding energy* of this system. It is usually denoted by letter B.

1.4.2 Nuclear energy units

The standart unit of energy, *Joule*, is too large to measure the energies associated with individual nuclei. This is why in nuclear physics it is more convenient to use a much smaller unit called Mega-electron-Volt (MeV). This is the amount of energy that an electron acquires after passing between two charged plates with the potential difference (voltage) of one million Volts. Sounds very huge, isn't it? But look at this relation

$$1\,\text{MeV} = 1.602 \times 10^{-13}\,\text{J}$$

and think again. In the units of MeV, most of the energies in nuclear world can be expressed by values with only few digits before decimal point and without ten to the power of something. For example, the binding energy of proton and neutron (which is the simplest nuclear system and is called *deuteron*) is

$$B_{pn} = 2.225\,\text{MeV} .$$

The simplicity of the numbers is not the only advantage of using the unit MeV. Another, more important advantage, comes from the fact that most of experiments in nuclear physics are collision experiments, where particles are accelerated by electric field and collide with other particles. From the above value of B_{pn}, for instance, we immediately know that in order to break up deuterons, we need to bombard them with a flux of electrons accelerated through a voltage not less than 2.225 million Volts. No calculation is needed! On the other hand, if we know that a charged particle (with a unit charge) passes through a voltage, say, 5 million Volts, we can, without any calculation, say that it acqures the energy of 5 MeV. It is very convenient. Isn't it?

1.4.3 Mass defect

Comparing the masses of atomic nuclei with the masses of the nucleons that constitute them, we encounter a surprising fact: Total mass of the nucleons is greater than mass of the nucleus! For example, for the deuteron we have

$$m_d < m_p + m_n \ ,$$

where m_d, m_p, and m_n are the masses of deuteron, proton, and neutron, respectively. The difference is rather small,

$$(m_p + m_n) - m_d = 3.968 \times 10^{-30}\,\mathrm{kg} \ ,$$

but on the nuclear scale is noticeable since the mass of proton, for example,

$$m_p = 1672.623 \times 10^{-30}\,\mathrm{kg}$$

is also very small. This phenomenon is called *"mass defect"*. Where the mass disappears to, when nucleons are bound?

To answer this question, we notice that the energy of a bound state is lower than the energy of free particles. Indeed, to liberate them from a bound complex, we have to give them some energy. Thinking in the opposite direction, we conclude that, when forming a bound state, the particles have to get rid of the energy excess, which is exactly equal to the binding energy. This is observed experimentally: When a proton captures a neutron to form a deuteron, the excess energy of 2.225 MeV is emitted via electromagnetic radiation.

A logical conclusion from the above comes by itself: When proton and neutron are bounding, some part of their mass disappears together with the energy that is carried away by the radiation. And in the opposite process, when we break up the deutron, we give it the energy, some part of which makes up the lost mass.

Albert Einstein came to the idea of the equivalence between the mass and energy long before any experimental evidences were found. In his theory of relativity, he showed that total energy E of a moving body with mass m is

$$E = \frac{mc^2}{\sqrt{1 - \dfrac{v^2}{c^2}}} \;, \tag{1.1}$$

where v is its velocity and c the speed of light. Applying this equation to a non-moving body ($v = 0$), we conclude that it possesses the *rest* energy

$$E_0 = mc^2 \tag{1.2}$$

simply because it has mass. As you will see, this very formula is the basis for making nuclear bombs and nuclear power stations!

All the development of physics and chemistry, preceding the theory of relativity, was based on the assumption that the mass and energy of a closed system are conserving in all possible processes and they are conserved separately. In reality, it turned out that the conserving quantity is the *mass-energy*,

$$E_{\text{kin}} + E_{\text{pot}} + E_{\text{rad}} + mc^2 = \text{const} \;,$$

i.e. the sum of kinetic energy, potential energy, the energy of radiation, and the mass of the system.

In chemical reactions the fraction of the mass that is transformed into other forms of energy (and vise versa), is so small that it is not detectable even in most precise measurements. In nuclear processes, however, the energy release is very often millions times higher and therefore is observable.

You should not think that mutual transformations of mass and energy are the features of only nuclear and atomic processes. If you break up a piece of rubber or chewing gum, for example, in two parts, then the sum of masses of these parts will be slightly larger than the mass of the whole piece. Of course we will not be able to detect this “mass defect” with our scales. But we can calculate it, using the Einstein formula (1.2). For this, we would need to measure somehow the mechanical work A used to break up the whole piece (i.e. the amount of energy supplied to it).

This can be done by measuring the force and displacement in the breaking process. Then, according to Eq. (1.2), the mass defect is

$$\Delta m = \frac{A}{c^2} \ .$$

To estimate possible effect, let us assume that we need to stretch a piece of rubber in 10 cm before it breaks, and the average force needed for this is 10 N (approximately 1 kg). Then

$$A = 10\,\mathrm{N} \times 0.1\,\mathrm{m} = 1\,\mathrm{J}\ ,$$

and hence

$$\Delta m = \frac{1\,\mathrm{J}}{(299792458\,\mathrm{m/s})^2} \approx 1.1 \times 10^{-17}\,\mathrm{kg}.$$

This is very small value for measuring with a scale, but huge as compared to typical masses of atoms and nuclei.

1.4.4 Nuclear masses

Apparently, an individual nucleus cannot be put on a scale to measure its mass. Then how can nuclear masses be measured?

This is done with the help of the devices called *mass spectrometers*. In them, a flux of identical nuclei, accelerated to a certain energy, is directed to a screen where it makes a visible mark. Before striking the screen, this flux passes through magnetic field, which is perpendicular to velocity of the nuclei. As a result, the flux is deflected to certain angle. The greater the mass, the smaller is the angle (because of inertia). Thus, measuring the displacement of the mark from the center of the screen, we can find the deflection angle and then calculate the mass.

Since mass and energy are equivalent, in nuclear physics it is customary to measure masses of all particles in the units of energy, namely, in MeV. Examples of masses of subatomic particles are given in Table 1.1. The values given in this table, are the energies to which the nuclear masses are equivalent via the Einstein formula (1.2).

There are several advantages of using the units of MeV to measure particle masses. First of all, like with nuclear energies, we avoid handling very small numbers that involve ten to the power of something. For example, if we were measuring

particle	number of protons	number of neutrons	mass (MeV)
e	0	0	0.511
p	1	0	938.272
n	0	1	939.566
${}^{2}_{1}$H	1	1	1875.613
${}^{3}_{1}$H	1	2	2808.920
${}^{3}_{2}$He	2	1	2808.391
${}^{4}_{2}$He	2	2	3727.378
${}^{7}_{3}$Li	3	4	6533.832
${}^{9}_{4}$Be	4	5	8392.748
${}^{12}_{6}$C	6	6	11174.860
${}^{16}_{8}$O	8	6	14895.077
${}^{238}_{92}$U	92	146	221695.831

Table 1.1: Masses of electron, nucleons, and some nuclei.

masses in kg, the electron mass would be $m_e = 9.1093897 \times 10^{-31}$ kg. When masses are given in the equivalent energy units, it is very easy to calculate the mass defect. Indeed, adding the masses of proton and neutron, given in the second and third rows of Table 1.1, and subtracting the mass of ${}^{2}_{1}$H, we obtain the binding energy 2.225 MeV of the deuteron without further ado. One more advantage comes from particle physics. In collisions of very fast moving particles new particles (like electrons) can be created from vacuum, i.e. kinetic energy is directly transformed into mass. If the mass is expressed in the energy units, we know how much energy is needed to create this or that particle, without calculations.

1.5 Radioactivity

As was said before, the nucleus experiences the intense struggle between the electric repulsion of protons and nuclear attraction of the nucleons to each other. It therefore should not be surprising that there are many nuclei that are unstable. They can spontaneously (i.e. without an external push) break in pieces. When the fragments reach the distances where the short range nuclear attraction disappears, they fiercely push each other away by the electric forces. Thus accelerated, they move in different directions like small bullets making destruction on their way. This is an example of nuclear radioactivity but there are several other varieties of radioactive decay.

1.5.1 Discovery of radioactivity

Nuclear radioactivity was discovered by Antoine Henri Becquerel in 1896. Following Wilhelm Roentgen who discovered the X-rays, Becquerel pursued his own investigations of these mysterious rays.

The material Becquerel chose to work with contained uranium. He found that the crystals containing uranium and exposed to sunlight, made images on photographic plates even wrapped in black paper. He mistakingly concluded that the sun's energy was being absorbed by the uranium which then emitted X-rays. The truth was revealed thanks to bad weather.

On the 26th and 27th of February 1896 the skies over Paris were overcast and the uranium crystals Becquerel intended to expose to the sun were returned to a drawer and put over (by chance) the photographic plates. On the first of March, Becquerel developed the plates and to his surprise, found that the images on them were clear and strong. Therefore the uranium emitted radiation without an external source of energy such as the sun. This was the first observation of the nuclear radioactivity.

Later, Becquerel demonstrated that the uranium radiation was similar to the X-rays but, unlike them, could be deflected by a magnetic field and therefore must consist of charged particles. For his discovery of radioactivity, Becquerel was awarded the 1903 Nobel Prize for physics.

1.5.2 Nuclear α, β, and γ rays

Classical experiment that revealed complex content of the nuclear radiation, was done as follows. The radium crystals (another radioactive element) were put at the bottom of a narrow straight channel made in a thick piece of lead and open at one side. The lead absorbed everything except the particles moving along the channel. This device therefore produced a flux of particles moving in one direction like bullets from a machine gun. In front of the channel was a photoplate that could register the particles.

Without the magnetic field, the image on the plate was in the form of one single dot. When the device was immersed into a perpendicular magnetic field, the flux of particles was split in three fluxes, which was reflected by three dots on the photographic plate.

One of the three fluxes was stright, while two others were deflected in opposite directions. This showed that the initial flux contained positive, negative, and neutral particles. They were named respectively the α, β, and γ particles.

The α-rays were found to be the ^{4}He nuclei, two protons and two neutrons bound together. They have weak penetrating ability, a few centimeters of air or a few sheets of paper can effectively block them. The β-rays proved to be electrons. They have a greater penetrating power than the α-particles and can penetrate 3 mm of aluminum. The γ-rays are not deflected because they are high energy photons. They have the same nature as the radio waves, visible light, and the X-rays, but have much shorter wavelength and therefore are much more energetic. Among the three, the γ-rays have the greatest penetrating power being able to pass through several centimeters of lead and still be detected on the other side.

1.5.3 Danger of the ionizing radiation

The α, β, and γ particles moving through matter, collide with atoms and knock out electrons from them, i.e. make positive ions out of the atoms. This is why these rays are called *ionizing radiation.*

Apart from ionizing the atoms, this radiation destroys molecules. For humans and all other organisms, this is the most dangerous feature of the radiation. Imagine thousands of tiny tiny bullets passing through your body and making destruction on their way. Although people do not feel any pain when exposed to nuclear radiation, it harms the cells of the body and thus can make people sick or even kill them. Illness can strike people years after their exposure to nuclear radiation. For example, the ionizing particles can randomly modify the DNA (long organic molecules that store all the information on how a particular cell should function in the body). As a result, some cells with wrong DNA may become cancer cells.

Fortunately, our body is able to repair some damages caused by radiation. Indeed, we are constantly bombarded by the radiation coming from the outer space as well as from the inner parts of our own planet and still survive. However, if the number of damages becomes too large, the body will not cope with them anymore.

There are established norms and acceptable limits for the radiation that are considered safe for human body. If you are going to work in contact with radioactive materials or near them, make sure that the exposure dose is monitored and the limits are adhered to.

You should understand that no costume can protect you from γ-rays! Only a thick wall of concrete or metal can stop them. The special costumes and masks that people wear when handling radioactive materials, protect them not from the rays but from contamination with that materials. Imagine if few specks of radioactive dirt stain your everyday clothes or if you inhale radioactive atoms. They will remain with you all the time and will shoot the "bullets" at you even when you are sleeping.

In many cases, a very effective way of protecting yourself from the radiation is to keep certain distance. Radiation from nuclear sources is distributed equally in all directions. Therefore the number n of dangerous particles passing every second through a unit area (say 1 cm^2) is the total number N of particles emitted during 1 second, divided by the surface of a sphere

$$n = \frac{N}{4\pi r^2} \ ,$$

where r is the distance at which we make the observation. From this simple formula, it is seen that the radiation intensity falls down with incresing distance quadratically. In other words, if you increase the distance by a factor of 2, your exposure to the radiation will be decreased by a factor of 4.

1.5.4 Decay law

Unstable nuclei decay spontaneously. A given nucleus can decay next moment, next day or even next century. Nobody can predict when it is going to happen. Despite this seemingly chaotic and "unscientific" situation, there is a strict order in all this.

Atomic nuclei, being microscopic objects, are ruled by quantum probabilistic laws. Although we cannot predict the exact moment of its decay, we can calculate the probability that a nucleus will decay within this or that time interval. Nuclei decay because of their internal dynamics and not because they become "old" or somehow "rotten".

To illustrate this, let us imagine that yesterday morning we found that a certain nucleus was going to decay within 24 hours with the probability of 50%. However, this morning we found that it is still "alive". This fact does not mean that the decay probability for another 24 hours increased. Not at all! It remains the same, 50%, because the nucleus remains the same, nothing wrong happened to it. This can go on and on for centuries.

Actually, we never deal with individual nuclei but rather with huge numbers of identical nuclei. For such collections (ensembles) of quantum objects, the probabilistic laws become statictical laws. Let us assume that in the above example we had 1 million identical nuclei instead of only one. Then by this morning only half of these nuclei would survive because the decay probability for 24 hours was 50%. Among the remaining 500000 nuclei, 250000 will decay by tomorrow morning, then after another 24 hours only 125000 will remain and so on.

The number of unstable nuclei that are still "alive" continuously decreases with time according to the curve shown in Fig. 1.2. If initially, at time $t = 0$, their number is N_0, then after certain time interval $T_{1/2}$ only half of these nuclei will remain, namely, $\frac{1}{2}N_0$. Another one half of the remaining half will decay during another such interval. So, after the time $2T_{1/2}$, we will have only one quarter of the initial amount, and so on. The time interval $T_{1/2}$, during which one half of unstable nuclei decay, is called their *half-life time*. It is specific for each unstable nucleus and vary from a fraction of a second to thousands and millions of years. A few examples of such lifetimes are given in Table 1.2

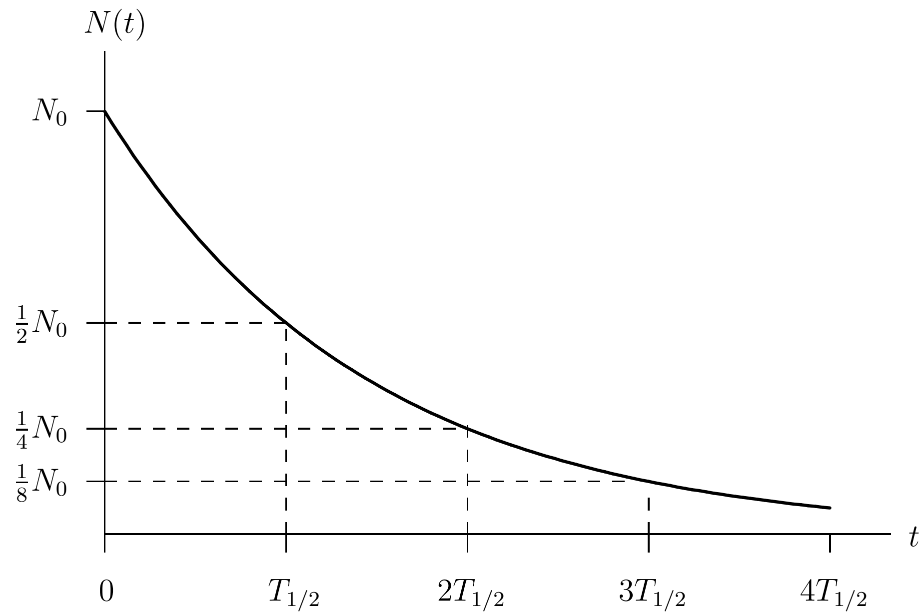


Figure 1.2: The time $T_{1/2}$ during which one half of the initial amount of unstable particles decay, is called their half-life time.

1.5.5 Radioactive dating

Examining the amounts of the decay products makes possible radioactive dating. The most famous is the *Carbon dating*, a variety of radioactive dating which is applicable only to matter which was once living and presumed to be in equilibrium with the atmosphere, taking in carbon dioxide from the air for photosynthesis.

Cosmic ray protons blast nuclei in the upper atmosphere, producing neutrons which in turn bombard nitrogen, the major constituent of the atmosphere. This neutron bombardment produces the radioactive isotope ${}^{14}_{6}$C. The radioactive carbon-14 combines with oxygen to form carbon dioxide and is incorporated into the cycle of living things.

The isotope ${}^{14}_{6}$C decays (see Table 1.2) inside living bodies but is replenished from the air and food. Therefore, while an organism is alive, the concentration of this isotope in the body remains constant. After death, the replenishment from

isotope	$T_{1/2}$	decay mode
${}^{214}_{84}\mathrm{Po}$	$1.64 \times 10^{-4}\,\mathrm{s}$	α, γ
${}^{89}_{36}\mathrm{Kr}$	$3.16\,\mathrm{min}$	β^-, γ
${}^{222}_{86}\mathrm{Rn}$	$3.83\,\mathrm{days}$	α, γ
${}^{90}_{38}\mathrm{Sr}$	$28.5\,\mathrm{years}$	β^-
${}^{226}_{88}\mathrm{Ra}$	$1.6 \times 10^3\,\mathrm{years}$	α, γ
${}^{14}_{6}\mathrm{C}$	$5.73 \times 10^3\,\mathrm{years}$	β^-
${}^{238}_{92}\mathrm{U}$	$4.47 \times 10^9\,\mathrm{years}$	α, γ
${}^{115}_{49}\mathrm{In}$	$4.41 \times 10^{14}\,\mathrm{years}$	β^-

Table 1.2: Half-life times of several unstable isotopes.

the breath and food stops, but the isotopes that are in the dead body continue to decay. As a result the concentration of ${}^{14}_{6}\mathrm{C}$ in it gradually decreases according to the curve shown in Fig. 1.2. The time $t = 0$ on this Figure corresponds to the moment of death, and N_0 is the equilibrium concentration of ${}^{14}_{6}\mathrm{C}$ in living organisms.

Therefore, by measuring the radioactive emissions from once-living matter and comparing its activity with the equilibrium level of emissions from things living today, an estimation of the time elapsed can be made. For example, if the rate of the radioactive emissions from a piece of wood, caused by the decay of ${}^{14}_{6}\mathrm{C}$, is one-half lower than from living trees, then we can conclude that we are at the point $t = T_{1/2}$ on the curve 1.2, i.e. it is elapsed exactly one half-life-time period. According to the Table 1.2), this means that the tree, from which this piece of wood was made, was cut approximately 5730 years ago. This is how physicists help archaeologists to assign dates to various organic materials.

1.6 Nuclear reactions

Those of you who studied chemistry, are familiar with the notion of chemical reaction, which, in essence, is just regrouping of atoms that constitute molecules. As a result, reagent chemical compounds are transformed into product compounds.

In the world of nuclear particles, similar processes are possible. When nuclei are close to each other, nucleons from one nucleus can "jump" into another one. This happens because there are attractive and repulsive forces between the nucleons. The complicated interplay of these forces may cause their regrouping. As a result, the reagent particles are transformed into product particles. Such processes are called *nuclear reactions*.

For example, when two isotopes ${}^3_2\mathrm{He}$ collide, the six nucleons constituting them, can rearrange in such a way that the isotope ${}^4_2\mathrm{He}$ is formed and two protons are liberated. Similarly to chemical reactions, this process is denoted as

$$
{}^3_2\mathrm{He} + {}^3_2\mathrm{He} \longrightarrow {}^4_2\mathrm{He} + p + p + 12.86\,\mathrm{MeV}\ . \tag{1.3}
$$

The same as in chemical reactions, nuclear reactions can also be either exothermic (i.e. releasing energy) or endothermic (i.e. requiring an energy input). The above reaction releases 12.86 MeV of energy. This is because the total mass on the left hand side of Eq. (1.3) is in 12.86 MeV greater than the total mass of the products on the right hand side (you can check this using Table 1.1).

Thus, when considering a particular nuclear reaction, we can always learn if it releases or absorbs energy. For this, we only need to compare total masses on the left and right hand sides of the equation. Now, you can understand why it is very convenient to express masses in the units of energy.

Composing equations like (1.3), we should always check the superscripts and subscripts of the nuclei in order to have the same number of nucleons and the same charge on both sides of the equation. In the above example, we have six nucleons and the charge +4 in both the initial and final states of the reaction. To make the checking of nucleon number and charge conservation easier, sometimes the proton and neutron are denoted with superscripts and subscripts as well, namely, ${}^1_1p$ and ${}^1_0n$. In this case, all we need is to check that sum of superscripts and sum of subscripts are the same on both sides of the equation.

1.7 Detectors

How can we observe such tiny tiny things as protons and α-particles? There is no microscope that would be able to discern them. From the very beginning of the subatomic era, scientists have been working on the development of special instruments that are called particle detectors. These devices enable us either to register the mere fact that certain particle has passed through certain point in space or to observe the trace of its path (the trajectory). Actually, this is as good as watching the particle. Although the particle sizes are awfully small, when passing through some substances, they leave behind visible traces of tens of centimeters in length. By measuring the curvature of the trajectory of a particle deflected in electric or magnetic field, a physicist can determine the charge and mass of the particle and thus can identify it.

1.7.1 Geiger counter

The most familiar device for registering charged particles is the Geiger counter. It cannot tell you anything about the particle except the fact that it has passed through the counter. The counter consists of a thin metal cylinder filled with gas. A wire electrode runs along the center of the tube and is kept at a high voltage ($\sim 2000\,\mathrm{V}$) relative to the cylinder. When a particle passes through the tube, it causes ionization of the gas atoms and thus an electric discharge between the cylinder and the wire. The electric pulse can be counted by a computer or made to produce a "click" in a loudspeaker. The number of counts per second tells us about intensity of the radiation.

1.7.2 Fluorescent screen

The very first detector was the fluorescent screen. When a charged particle hits the screen, a human eye can discern a flash of light at the point of impact. In fact, we all use this kind of detectors every day when watching TV of looking at a computer (if it does not have an LCD screen of course). Indeed, the images on the screens of their electron-ray tubes are formed by the accelerated electrons.

1.7.3 Photo-emulsion

Another type of particle detector, dating back to Becquerel, is the nuclear photographic emulsion. Passage of charged particles is recorded in the emulsion in the same way that ordinary black and white photographic film records a picture. The only difference is that nuclear photoemulsion is made rather thick in order to catch a significant part of the particle path. After the developing, a permanent record of the charged particle trajectory is available.

1.7.4 Wilson's chamber

In the fields of sub-atomic physics and nuclear physics, Wilson's cloud chamber is the most fundamental device to observe the trajectories of particles. Its basic principle was discovered by C. T. R. Wilson in 1897, and it was put to the practical use in 1911.

The top and the side of the chamber are covered with round glasses of several centimeters in diameter. At the bottom of the chamber, a piston is placed. The air filled in the chamber is saturated with vapor of water. When pulling down the piston quickly, the volume of the chamber would be expanded and the temperature goes down. As a result, the air inside would be supersaturated with the vapor. If a fast moving charged particle enters the chamber when it is in such a supersaturated state, the vapor of water would condense along the line of the ions generated by the particle, which is the path of the particle. Thus we can observe the trace, and also take a photograph. To make clear the trace, a light is sometimes illuminated from the side. When placing the cloud chamber in a magnetic field, we can obtain various informations about the charged particle by measuring the curvature of the trace and other data. The bubble chamber and the spark chamber have taken place of the cloud chamber which is nowadays used only for the educational purposes. Wilson's cloud chamber has however played a very important role in the history of physics.

1.7.5 Bubble chamber

Bubble chamber is a particle detector of major importance during the initial years of high-energy physics. The bubble chamber has produced a wealth of physics from about 1955 well into the 1970s. It is based on the principle of bubble formation in a liquid heated above its boiling point, which is then suddenly expanded, starting boiling where passing charged particles have ionized the atoms of the liquid. The technique was honoured by the Nobel prize award to D. Glaser in 1960. Even today, bubble chamber photographs provide the aesthetically most appealing visualization of subnuclear collisions.

1.7.6 Spark chamber

Spark chamber is a historic device using electric discharges over a gap between two electrodes with large potential difference, to render passing particles visible. Sparks occurred where the gas had been ionized. Most often, multiple short gaps were used, but wide-gap chambers with gaps up to 40 cm were also built. The spark chamber is still of great scientific value in that it remains relatively simple and cheap to build as well as enabling an observer to view the paths of charged particles.

1.8 Nuclear energy

Nuclei can produce energy via two different types of reactions, namely, *fission* and *fusion* reactions. Fission is a break up of a nucleus in two or more pieces (smaller nuclei). Fusion is the opposite process: Formation of a bigger nucleus from two small nuclei.

A question may arise: How two opposite processes can both produce energy? Can we make an inexhaustible souce of energy by breaking up and then fusing the same nuclei? Of cousre not! The energy conservation law cannot be circumvented in no way. When speaking about fusion and fission, we speak about different ranges of nuclei. Energy can only be released when either light nuclei fuse or heavy nuclei fission.

To understand why this is so, let us recollect that for releasing energy the mass of initial nuclei must be greater than the mass of the products of a nuclear reaction. The mass difference is transformed into the released energy. And why the product nuclei can loose some mass as compared to the initial nuclei? Because they are more tightly bound, i.e. their binding energies are lager.

Fig. 1.3 shows the dependence of the binding energy B per nucleon on the number A of nucleons constituting a nucleus. As you see, the curve reaches the maximum value of $\sim 9\,\mathrm{MeV}$ per nucleon at around $A \sim 50$. The nuclei with such number of nucleons cannot produce energy neither through fusion nor through fission. They are kind of "ashes" and cannot serve as a fuel. In contrast to them, very light nuclei, when fused with each other, make more tightly bound products as well as very heavy nuclei do when split up in lighter fragments.

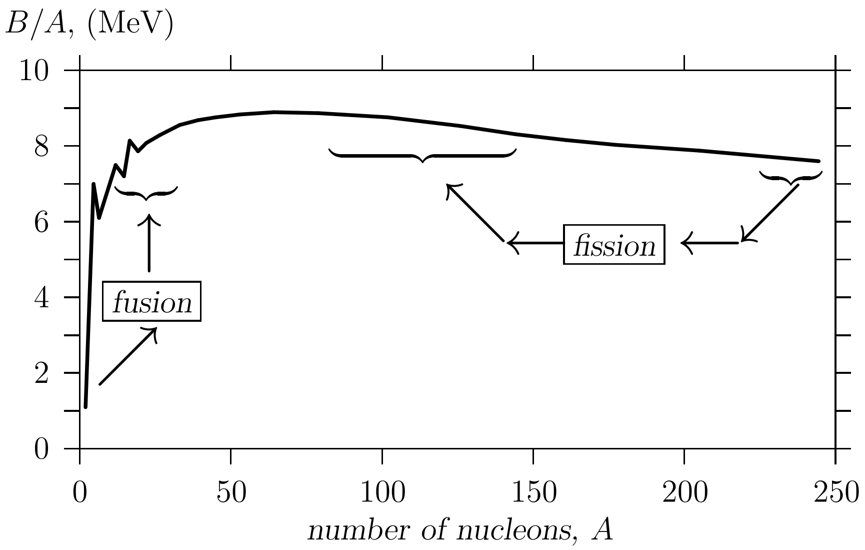


Figure 1.3: Binding energy per nucleon.

In fission processes, which were discovered and used first, a heavy nucleus like, for example, uranium or plutonium, splits up in two fragments which are both positively charged. These fragments repel each other by an electric force and move apart at a high speed, distributing their kinetic energy in the surrounding material.

In fusion reactions everything goes in the opposite direction. Very light nuclei, like hydrogen or helium isotopes, when approaching each other to a distance of a few fm ($1\,\mathrm{fm} = 10^{-13}\,\mathrm{cm}$), experience strong attraction which overpowers their Coulomb (that is electric) repulsion. As a result the two nuclei fuse into a single nucleus. They collapse with extremely high speeds towards each other. To form a stable nucleus they must get rid of the excessive energy. This energy is emitted by ejecting a neutron or a photon.

1.8.1 Nuclear reactors

Since the discovery of radioactivity it was known that heavy nuclei release energy in the processes of spontaneous decay. This process, however, is rather slow and cannot be influenced (speed up or slow down) by humans and therefore could not be effectively used for large-scale energy production. Nonetheless, it is ideal for feeding the devices that must work autonomously in remote places for a long time and do not require much energy. For this, heat from the spontaneous-decays can be converted into electric power in a radioisotope thermoelectric generator. These generators have been used to power space probes and some lighthouses built by Russian engineers. Much more effective way of using nuclear energy is based on another type of nuclear decay which is considered next.

Chain reaction

The discovery that opened up the era of nuclear energy was made in 1939 by German physicists O. Hahn, L. Meitner, F Strassmann, and O. Frisch. They found that a uranium nucleus, after absorbing a neutron, splits into two fragments. This was not a spontaneous but induced fission

$$n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + n + n + 185\,\mathrm{MeV} \tag{1.4}$$

that released $\sim 185\,\mathrm{MeV}$ of energy as well as two neutrons which could cause similar reactions on surrounding nuclei. The fact that instead of one initial neutron, in the reaction (1.4) we obtain two neutrons, is crucial. This gives us the possibility to make the so-called *chain reaction* schematically shown in Fig. 1.4.

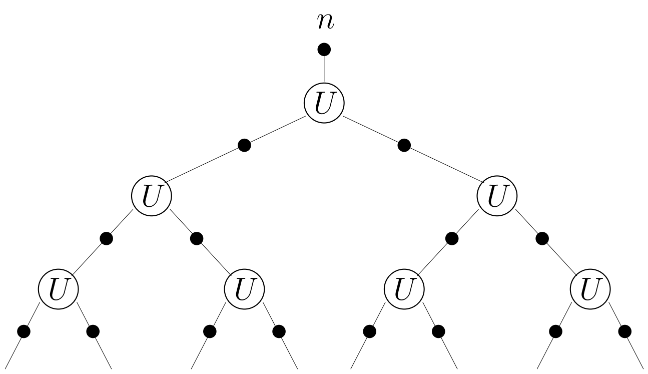


Figure 1.4: Chain reaction on uranium nuclei.

In such process, one neutron breaks one heavy nucleus, the two released neutrons break two more heavy nuclei and produce four neutrons which, in turn, can break another four nuclei and so on. This process develops extremely fast. In a split of a second a huge amount of energy can be released, which means explosion. In fact, this is how the so-called atomic bomb works.

Can we control the development of the chain reaction? Yes we can! This is done in nuclear reactors that produce energy for our use. How can it be done?

Critical mass

First of all, if the piece of material containing fissile nuclei is too small, some neutrons may reach its surface and escape without causing further fissions. For each type of fissile material there is therefore a minimal mass of a sample that can support explosive chain reaction. It is called the *critical mass.* For example, the critical mass of $^{235}_{92}\mathrm{U}$ is approximately 50 kg. If the mass is below the critical value, nuclear explosion is not possible, but the energy is still released and the sample becomes hot. The closer mass is to its critical value, the more energy is released and more intensive is the neutron radiation from the sample.

The criticality of a sample (i.e. its closeness to the critical state) can be reduced by changing its geometry (making its surface bigger) or by putting inside it some other material (boron or cadmium) that is able to absorb neutrons. On the other hand, the criticality can be increased by putting neutron reflectors around the sample. These reflectors work like mirrors from which the escaped neutrons bounce back into the sample. Thus, moving in and out the absorbing material and reflectors, we can keep the sample close to the critical state.

How a nuclear reactor works

In a typical nuclear reactor, the fuel is not in one piece, but in the form of several hundred vertical rods, like a brush. Another system of rods that contain a neutron absorbing material (control rods) can move up and down in between the fuel rods. When totally in, the control rods absorb so many neutrons, that the reactor is shut down. To start the reactor, operator gradually moves the control rods up. In an emergency situation they are dropped down automatically.

To collect the energy, water flows through the reactor core. It becomes extremely hot and goes to a steam generator. There, the heat passes to water in a secondary circuit that becomes steam for use outside the reactor enclosure for rotating turbines that generate electricity.

Nuclear power in South Africa

By 2004 South Africa had only one commercial nuclear reactor supplying power into the national grid. It works in Koeberg located 30 km north of Cape Town. A small research reactor was also operated at Pelindaba as part of the nuclear weapons program, but was dismantled.

Koeberg Nuclear Power station is a uranium Pressurized Water Reactor (PWR). In such a reactor, the primary coolant loop is pressurised so the water does not boil, and heat exchangers, called steam generators, are used to transmit heat to a secondary coolant which is allowed to boil to produce steam. To remove as much heat as possible, the water temperature in the primary loop is allowed to rise up to about 300 °C which requires the pressure of 150 atmospheres (to keep water from boiling).

The Koeberg power station has the largest turbine generators in the southern hemisphere and produces $\sim$10000 MWh of electric energy. Construction of Koeberg began in 1976 and two of its Units were commissioned in 1984-1985. Since then, the plant has been in more or less continuous operation and there have been no serious incidents.

Eskom that operates this power station, may be the current technology leader. It is developing a new type of nuclear reactor, a modular pebble-bed reactor (PBMR). In contrast to traditional nuclear reactors, in this new type of reactors the fuel is not assembled in the form of rods. The uranium, thorium or plutonium fuels are in oxides (ceramic form) contained within spherical pebbles made of pyrolitic graphite. The pebbles, having a size of a tennis ball, are in a bin or can. An inert gas, helium, nitrogen or carbon dioxide, circulates through the spaces between the fuel pebbles. This carries heat away from the reactor.

Ideally, the heated gas is run directly through a turbine. However since the gas from the primary coolant can be made radioactive by the neutrons in the reactor, usually it is brought to a heat exchanger, where it heats another gas, or steam.

The primary advantage of pebble-bed reactors is that they can be designed to be inherently safe. When a pebble-bed reactor gets hotter, the more rapid motion of the atoms in the fuel increases the probability of neutron capture by ${}^{238}_{92}\mathrm{U}$ isotopes through an effect known as Doppler broadening. This isotope does not split up after capturing a neutron. This reduces the number of neutrons available to cause $^{235}_{92}U$ fission, reducing the power output by the reactor. This natural negative feedback places an inherent upper limit on the temperature of the fuel without any operator intervention.

The reactor is cooled by an inert, fireproof gas, so it cannot have a steam explosion as a water reactor can.

A pebble-bed reactor thus can have all of its supporting machinery fail, and the reactor will not crack, melt, explode or spew hazardous wastes. It simply goes up to a designed "idle" temperature, and stays there. In that state, the reactor vessel radiates heat, but the vessel and fuel spheres remain intact and undamaged. The machinery can be repaired or the fuel can be removed.

A large advantage of the pebble bed reactor over a conventional water reactor is that they operate at higher temperatures. The reactor can directly heat fluids for low pressure gas turbines. The high temperatures permit systems to get more mechanical energy from the same amount of thermal energy.

Another advantage is that fuel pebbles for different fuels might be used in the same basic design of reactor (though perhaps not at the same time). Proponents claim that some kinds of pebble-bed reactors should be able to use thorium, plutonium and natural unenriched Uranium, as well as the customary enriched uranium. One of the projects in progress is to develop pebbles and reactors that use the plutonium from surplus or expired nuclear explosives.

On June 25, 2003, the South African Republic's Department of Environmental Affairs and Tourism approved ESKOM's prototype 110 MW pebble-bed modular reactor for Koeberg. Eskom also has approval for a pebble-bed fuel production plant in Pelindaba. The uranium for this fuel is to be imported from Russia. If the trial is successful, Eskom says it will build up to ten local PBMR plants on South Africa's seacoast. Eskom also wants to export up to 20 PBMR plants per year. The estimated export revenue is 8 billion rand a year, and could employ about 57000 people.

1.8.2 Fusion energy

For a given mass of fuel, a fusion reaction like

$$^2_1\mathrm{H} + {}^3_1\mathrm{H} \longrightarrow {}^4_2\mathrm{He} + n + 17.59\,\mathrm{MeV}\ . \tag{1.5}$$

yield several times more energy than a fission reaction. This is clear from the curve given in Fig. 1.3. Indeed, a change of the binding energy (per nucleon) is much more significant for a fusion reaction than for a fission reaction. Fusion is, therefore, a much more powerful source of energy. For example, 10 g of Deuterium which can be extracted from 500 litres of water and 15 g of Tritium produced from 30 g of Lithium would give enough fuel for the lifetime electricity needs of an average person in an industrialised country.

But this is not the only reason why fusion attracted so much attention from physicists. Another, more fundamental, reason is that the fusion reactions were responsible for the synthesis of the initial amount of light elements at primordial times when the universe was created. Furthermore, the synthesis of nuclei continues inside the stars where the fusion reactions produce all the energy which reaches us in the form of light.

Thermonuclear reactions

If fusion is so advantageous, why is it not used instead of fission reactors? The problem is in the electric repulsion of the nuclei. Before the nuclei on the left hand side of Eq. (1.5) can fuse, we have to bring them somehow close to each other to a distance of $\sim 10^{-13}$ cm. This is not an easy task! They both are positively charged and "refuse" to approach each other.

What we can do is to make a mixture of the atoms containing such nuclei and heat it up. At high temperatures the atoms move very fast. They fiercely collide and loose all the electrons. The mixture becomes *plasma*, i.e. a mixture of bare nuclei and free moving electrons. If the temperature is high enough, the colliding nuclei can overcome the electric repulsion and approach each other to a fusion distance.

When the nuclei fuse, they release much more energy than was spent to heat up the plasma. Thus the initial energy "investment" pays off. The typical temperature needed to ignite the reaction of the type (1.5) is extremely high. In fact, it is the same temperature that our sun has in its center, namely, $\sim$15 million degrees. This is why the reactions (1.3), (1.5), and the like are called *thermonuclear reactions*.

Human-made thermonuclear reactions

The same as with fission reactions, the first application of thermonuclear reactions was in weapons, namely, in the hydrogen bomb, where fusion is ignited by the explosion of an ordinary (fission) plutonium bomb which heats up the fuel to solar temperatures.

In an attempt to make a controllable fusion, people encounter the problem of holding the plasma. It is relatively easy to achieve a high temperature (with laser pulses, for example). But as soon as plasma touches the walls of the container, it immediately cools down. To keep it from touching the walls, various ingenious methods are tried, such as strong magnetic field and laser beams directed to plasma from all sides. In spite of all efforts and ingenious tricks, all such attempts till now have failed. Most probably this straightforward approach to controllable fusion is doomed because one has to hold in hands a "piece of burning sun".

Cold fusion

To visualize the struggle of the nuclei approaching each other, imagine yourself pushing a metallic ball towards the top of a slope shown in Fig. 1.5. The more kinetic energy you give to the ball, the higher it can climb. Your purpose is to make it fall into the narrow well that is behind the barrier.

In fact, the curve in Fig. 1.5 shows the dependence of relative potential energy V_{eff} between two nuclei on the distance R separating them. The deep narrow well corresponds to the strong short-range attraction, and the $\sim 1/R$ barrier represents the Coulomb (electric) repulsion. The nuclei need to overcome this barrier in order to "touch" each other and fuse, i.e. to fall into the narrow and deep potential well. One way to achieve this is to give them enough kinetic energy, which means to rise the temperature. However, there is another way based on the quantum laws.

As you remember, when discussing the motion of the electron inside an atom (see Sec. 1.1), we said that it formed a "cloud" of probability around the nucleus. The density of this cloud diminishes at very short and very long distances but never

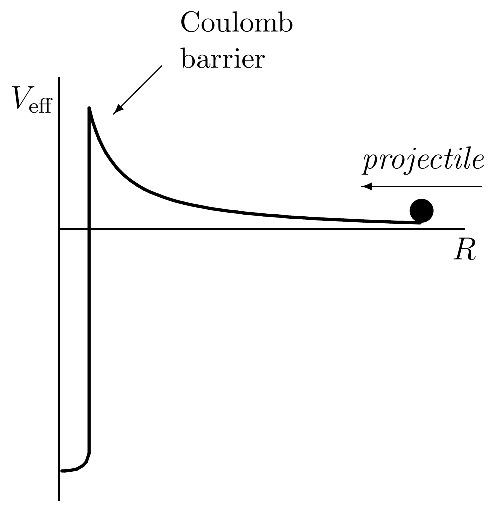


Figure 1.5: Effective nucleus–nucleus potential as a function of the separation between the nuclei.

disappears completely. This means that we can find the electron even inside the nucleus though with a rather small probability.

The nuclei moving towards each other, being microscopic objects, obey the quantum laws as well. The probability density for finding one nucleus at a distance R from another one also forms a cloud. This density is non-zero even under the barrier and on the other side of the barrier. This means that, in contrast to classical objects, quantum particles, like nuclei, can penetrate through potential barriers even if they do not have enough energy to go over it! This is called the *tunneling effect.*

The tunneling probability strongly depends on thickness of the barrier. Therefore, instead of lifting the nuclei against the barrier (which means rising the temperature), we can try to make the barrier itself thinner or to keep them close to the barrier for such a long time that even a low penetration probability would be realized.

How can this be done? The idea is to put the nuclei we want to fuse, inside a molecule where they can stay close to each other for a long time. Furthermore, in a molecule, the Coulomb barrier becomes thinner because of electron screening. In this way fusion may proceed even at room temperature.

This idea of *cold fusion* was originally (in 1947) discussed by F. C. Frank and (in 1948) put forward by A. D. Sakharov, the "father" of Russian hydrogen bomb, who at the latest stages of his career was worldwide known as a prominent human rights activist and a winner of the Nobel Prize for Peace. When working on the bomb project, he initiated research into peaceful applications of nuclear energy and suggested the fusion of two hydrogen isotopes via the reaction (1.5) by forming a molecule of them where one of the electrons is replaced by a muon.

The muon is an elementary particle (see Sec. 1.9), which has the same characteristics as an electron. The only difference between them is that the muon is 200 times heavier than the electron. In other words, a muon is a heavy electron. What will happen if we make a muonic atom of hydrogen, that is a bound state of a proton and a muon? Due to its large mass the muon would be very close to the proton and the size of such atom would be 200 times smaller than that of an ordinary atom. This is clearly seen from the formula for the atomic Bohr radius

$$R_{\text{Bohr}} = \frac{\hbar^2}{me^2} \ ,$$

where the mass is in the denominator.

Now, what happens if we make a muonic molecule? It will also be 200 times smaller than an ordinary molecule. The Coulomb barrier will be 200 times thinner and the nuclei 200 times closer to each other. This is just what we need! Speaking in terms of the effective nucleus–nucleus potential shown in Fig. 1.5, we can say that the muon modifies this potential in such a way that a second minimum appears. Such a modified potential is (schematically) shown in Fig. 1.6.

The molecule is a bound state in the shallow but wide minimum of this potential. Most of the time, the nuclei are at the distance corresponding to the maximum of the probability density distribution (shown by the thin curve). Observe that this density is not zero under the barrier (though is rather small) and even at $R = 0$. This means that the system can (with a small probability) jump from the shallow well into the deep well through the barrier, i.e. can tunnel and fuse.

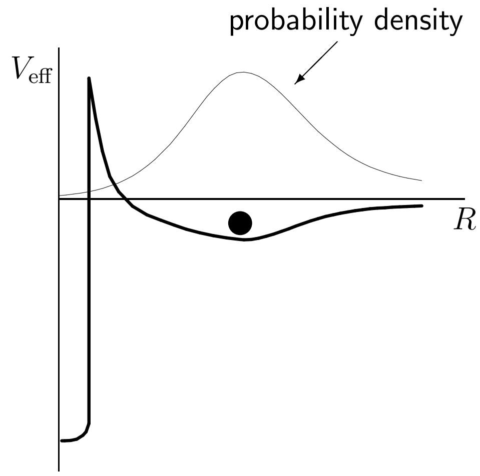


Figure 1.6: Effective nucleus–nucleus potential (thick curve) for nuclei confined in a molecule. Thin curve shows the corresponding distribution of the probability for finding the nuclei at a given distance from each other.

Unfortunately, the muon is not a stable particle. Its lifetime is only $\sim 10^{-6}$ sec. This means that a muonic molecule cannot exist longer than 1 microsecond. As a matter of fact, from a quantum mechanical point of view, this is quite a long interval.

The quantum mechanical wave function (that describes the probability density) oscillates with a frequency which is proportional to the energy of the system. With a typical binding energy of a muonic molecule of 300 eV this frequency is $\sim 10^{17}\,\text{s}^{-1}$. This means that the particle hits the barrier with this frequency and during 1 microsecond it makes 10^{11} attempts to jump through it. The calculations show that the penetration probability is $\sim 10^{-7}$. Therefore, during 1 microsecond nuclei can penetrate through the barrier 10000 times and fusion can happen much faster than the decay rate of the muon.

Cold fusion via the formation of muonic molecules was done in many laboratories, but unfortunately, it cannot solve the problem of energy production for our needs. The obstacle is the negative efficiency, *i.e.* to make muonic cold fusion we have to spend more energy than it produces. The reason is that muons do not exist like protons or electrons. We have to produce them in accelerators. This takes a lot of energy.

Actually, the muon serves as a catalyst for the fusion reaction. After helping one pair of nuclei to fuse, the muon is liberated from the molecule and can form another molecule, and so on. It was estimated that the efficiency of the energy production would be positive only if each muon ignited at least 1000 fusion events. Experimentalists tried their best, but by now the record number is only 150 fusion events per muon. This is too few. The main reason why the muon does not catalyze more reactions is that it is eventually trapped by a ^{4}He nucleus which is a by-product of fusion. Helium captures the muon into an atomic orbit with large binding energy, and it cannot escape.

Nonetheless, the research in the field of cold fusion continues. There are some other ideas of how to keep nuclei close to each other. One of them is to put the nuclei inside a crystal. Another way out is to increase the penetration probability by using molecules with special properties, namely, those that have quantum states with almost the same energies as the excited states on the compound nucleus. Scientists try all possibilities since the energy demands of mankind grow continuously and therefore the stakes in this quest are high.

1.9 Elementary particles

In our quest for the elementary building blocks of the universe, we delved inside atomic nucleus and found that it is composed of protons and neutrons. Are the three particles, e, p, and n, the blocks we are looking for? The answer is "no". Even before the structure of the atom was understood, Becquerel discovered the redioactivity (see Sec. 1.5.1) that afterwards puzzled physicists and forced them to look deeper, i.e. inside protons and neutrons.

1.9.1 β decay

Among the three types of radioactivity, the α and γ rays were easily explained. The emission of α particle is kind of fission reaction, when an initial nucleus spontaneously decays in two fragments one of which is the nucleus $^4_2$He (i.e. α particle). The γ rays are just electromagnetic quanta emitted by a nuclear system when it transits from one quantum state to another (the same like an atom emits light).

The β rays posed the puzzle. On the one hand, they are just electrons and you may think that it looks simple. But on the other hand, they are not the electrons from the atomic shell. It was found that they come from inside the nucleus! After the β-decay, the charge of the nucleus increases in one unit,

$$ {}^{A}_{Z}\,(\mathsf{parent\ nucleus}) \longrightarrow {}_{Z+1}^{\ \ A}\,(\mathsf{daughter\ nucleus}) + e \ , $$

which is in accordance with the charge conservation law.

There was another puzzle associated with the β decay: The emitted electrons did not have a certain energy. Measuring their kinetic energies, you could find very fast and very slow electrons as well as the electrons with all intermediate speeds. How could identical parent nuclei, after loosing different amount of energy, become identical daughter nuclei. May be energy is not conserving in the quantum world? The fact was so astonishing that even Niels Bohr put forward the idea of statistical nature of the energy conservation law.

To explain the first puzzle, it was naively suggested that neutron is a bound state of proton and electron. At that time, physicists believed that if something is emitted from an object, this something must be present inside that object before the emission. They could not imagine that a particle could be created from vacuum.

The naive (pe) model of the neutron contradicted the facts. Indeed, it was known already that the pe bound state is the hydrogen atom. Neutron is much smaller than the atom. Therefore, it would be unusually tight binding, and perhaps with something elese involved that keeps the size small. By the way, this "something elese" could also save the energy conservation law. In 1930, Wolfgang Pauli suggested that in addition to the electron, the β decay involves another particle, ν, that is emitted along with the electron and carries away part of the energy. For example,

$$ {}^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + e^- + \bar{\nu} \ . \qquad (1.6) $$

This additional particle was called *neutrino* (in Italian the word "neutrino" means small neutron). The neutrino is electrically neutral, has extremely small mass (maybe even zero, which is still a question in 2004) and very weakly interacts with matter. This is why it was not detected experimentally till 1956. The "bar" over ν in Eq. (1.6) means that in this reaction actually the anti-neutrino is emitted (see the discussion on anti-particles further down in Sec. 1.9.2).

1.9.2 Particle physics

In an attempt to explain the β decay and to understand internal structure of the neutron a new branch of physics was born, the *particle physics*. The only way to explore the structure of sub-atomic particles is to strike them with other particles in order to knock out their "constituent" parts. The simple logic says: The more powerful the impact, the smaller parts can be knocked out.

At the beginning the only source of energetic particles to strike other particles were the cosmic rays. Earth is constantly bombarded by all sort of particles coming from the outer space. Atmosphere protects us from most of them, but many still reach the ground.

Antiparticles

In 1932, studying the cosmic rays with a bubble chamber, Carl Anderson made a photograph of two symmetrical tracks of charged particles. The measurements of the track curvatures showed that one track belonged to an electron and the other was made by a particle having the same mass and equal but positive charge. These particles were created when a cosmic γ quantum of a high energy collided with a nucleus.

The discovered particle was called *positron* and denoted as e^+ to distinguish it from the electron, which sometimes is denoted as e^-. It was the first antiparticle discovered. Later, it was found that every particle has its "mirror reflection", the antiparticle. To denote an antiparticle, it is used "bar" over a particle symbol. For example, $\bar{p}$ is the anti-proton, which has the same mass as an ordinary proton but a negative charge.

When a particle collides with its "mirror reflection", they annihilate, i.e. they burn out completely. In this collision, all their mass is transformed into electromagnetic energy in the form of γ quanta. For example, if an electron collides with a positron, the following reaction may take place

$$e^- + e^+ \longrightarrow \gamma + \gamma \; , \tag{1.7}$$

where two photons are needed to conserve the total momentum of the system.

In principle, stable antimatter can exist. For example, the pair of $\bar{p}$ and e^+ can form an atom of anti-hydrogen with exactly the same energy states as the ordinary hydrogen. Experimentally, atoms of anti-helium were obtained. The problem with them is that, surrounded by ordinary matter, they cannot live long. Colliding with ordinary atoms, they annihilate very fast.

There are speculations that our universe should be symmetric with respect to particles and antiparticles. Indeed, why should preference be given to matter and not to anti-matter? This implies that somewhere very far, there must be equal amount of anti-matter, i.e. anti-universe. Can you imagine what happens if they meet?

Muon, mesons, and the others

In yet another cosmic-ray experiment a particle having the same properties as the electron but $\sim$207 times heavier, was discovered in 1935. It was given the name *muon* and the symbol μ. For a long time it remained "unnecessary" particle in the picture of the world. Only the modern theories harmonically included the muon as a constituent part of matter (see Sec 1.9.3).

The same inexhaustible cosmic rays revealed the π and K mesons in 1947. The π mesons (or simply *pions*) were theoretically predicted twelve years before by Yukawa, as the mediators of the strong forces between nucleons. The K mesons, however, were unexpected. Furthermore, they showed very strange behaviour. They were easily created only in pairs. The probability of the inverse process (i.e. their decay) was 10^{13} times lower than the probability of their creation.

It was suggested that these particles possess a new type of charge, the *strangeness*, which is conserving in the strong interactions. When a pair of such particles is created, one of them has strangeness $+1$ and the other -1, so the total strangeness remains zero. When decaying, they act individually and therefore the strangeness is not conserving. According to the suggestion, this is only possible through the weak interactions that are much weaker than the strong interactions (see Sec. 1.9.4) and thus the decay probability is much lower.

The golden age of particle physics began in 1950-s with the advent of particle accelerators, the machines that produced beams of electrons or protons with high kinetic energy. Having such beams available, experimentalists can plan the experiment and repeat it, while with the cosmic rays they were at the mercy of chance. When the accelerators became the main tool of exploration, the particle physics acquired its second name, the *high energy physics*.

During the last half a century, experimentalists discovered so many new particles (few of them are listed in Table 1.3) that it became obvious that they cannot all be elementary. When colliding with each other, they produce some other particles. Mutual transformations of the particles is their main property.

family	particle	symbol	mass (MeV)	Lifetime $T_{1/2}$ (s)
photon	photon	γ	0	stable
leptons	electron	e^-, e^+	0.511	stable
	muon	μ^-, μ^+	105.7	2.2×10^{-6}
	tau	τ^-, τ^+	1777	10^{-13}
	electron neutrino	ν_e	~ 0	stable
	muon neutrino	ν_μ	~ 0	stable
	tau neutrino	ν_τ	~ 0	stable
hadrons	pion	π^+, π^-	139.6	2.6×10^{-8}
	pion	π^0	135.0	0.8×10^{-16}
	kaon	K^+, K^-	493.7	1.2×10^{-8}
	kaon	K^0_S	497.7	0.9×10^{-10}
	kaon	K^0_L	497.7	5.2×10^{-8}
	eta meson	η^0	548.8	10^{-18}
	proton	p	938.3	stable
	neutron	n	939.6	900
	lambda	Λ^0	1116	2.6×10^{-10}
	sigma	Σ^+	1189	0.8×10^{-10}
	sigma	Σ^0	1192	6×10^{-20}
	sigma	Σ^-	1197	1.5×10^{-10}
	omega	Ω^-, Ω^+	1672	0.8×10^{-10}

Table 1.3: Few representatives of different particle families.

Physicists faced the problem of particle classification similar to the problems of classification of animals, plants, and chemical elements. The first approach was very simple. The particles were divided in four groups according to their mass: *leptons* (light particles, like electron), *mesons* (intermediate mass, like pion), *baryons* (heavy particles, like proton or neutron), and *hyperons* (very heavy particles).

Then it was realized that it would be more logical to divide the particles in three families according to their ability to interact via weak, electromagnetic, and strong forces (in addition to that, all particles experience gravitational attraction towards each other). Except for the gravitational interaction, the photon (γ quantum) participates only in electromagnetic interactions, the leptons take part in both weak and electromagnetic interactions, and *hadrons* are able to interact via all forces of nature (see Sec. 1.9.4).

In addition to conservation of the strangeness, several other conservation laws were discovered. For example, number of leptons is conserving. This is why in the reaction (1.6) we have an electron (lepton number $+1$) and anti-neutrino (lepton number -1) in the final state. Similarly, the number of baryons is conserving in all reactions.

The quest for the constituent parts of the neutron has led us to something unexpected. We found that there are several hundreds of different particles that can be "knocked out" of the neutron but none of them are its parts. Actually, the neutron itself can be knocked out of some of them! What a mess! Further efforts of experimentalists could not find an order, which was finally discovered by theoreticians who introduced the notion of *quarks*.

1.9.3 Quarks and leptons

While experimentalists seemed to be lost in the maze, the theoreticians groped for the way out. Using an extremely complicated mathematical technique, they managed to group the hadrons in such families which implied that all known (and yet unknown) hadrons are build of only six types of particles with fractional charges. The main credit for this (in the form of Nobel Prize) was given to M. Gell-Mann and G. Zweig.

At first, they considered a subset of the hadrons and developed a theory with only three types of such truly elementary particles. When Murray Gell-Mann thought of the name for them, he came across the book "Finnegan's Wake" by James Joyce. The line "Three quarks for Mister Mark..." appeared in that fanciful book (in German, the word "quark" means cottage cheese). He needed a name for three particles and this was the answer. Thus the term *quark* was coined.

Later, the theory was generalized to include all known particles, which required six types of quarks. Modern theories require also that the number of different leptons should be the same as the number of different quark types. According to these theories, the quarks and leptons are truly elementary, i.e. they do not have any internal structure and therefore are of a zero size (pointlike). Thus, the world is constructed of just twelve types of elementary building blocks that are given in Table 1.4. Amazingly enough, the electron that was discovered before all other particles, more than a century ago, turned out to be one of them!

family	elementary particle	symbol	charge	lepton number	baryon number	mass (MeV)
leptons	electron	e^-	-1	1	0	0.511
	muon	μ^-	-1	1	0	105.7
	tau	τ^-	-1	1	0	1777
	electron neutrino	ν_e	0	1	0	~ 0
	muon neutrino	ν_μ	0	1	0	~ 0
	tau neutrino	ν_τ	0	1	0	~ 0
quarks	up	u	$+2/3$	0	1/3	360
	down	d	$-1/3$	0	1/3	360
	strange	s	$-1/3$	0	1/3	1500
	charmed	c	$+2/3$	0	1/3	540
	top (truth)	t	$+2/3$	0	1/3	174000
	bottom (beauty)	b	$-1/3$	0	1/3	5000

Table 1.4: Elementary building blocks of the universe.

After Gell-Mann, who used a funny name (quark) for an elementary particle, the fundamental physics was flooded with such names. For example, the six quark types are called *flavors* (for cottage cheese, this is appropriate indeed), the three different states in which each quark can be, are called *colors* (red, green, blue), etc. Modern physics is so complicated and mathematical, that people working in it, need such kind of jokes to "spice unsavoury dish with flavors". The funny names should not confuse anybody. Elementary particles do not have any smell, taste, or colour. These terms simply denote certain properties (similar to electric charge) that do not exist in human world.

Hadrons

There are particles that are able to interact with each other by the so-called *strong forces*. Another name for these forces is *nuclear forces*. They are very strong at short distances ($\sim 10^{-15}\,\mathrm{m}$), and very quickly vanish when the distance between the particles increases. All these particles are called *hadrons*. The protons and neutrons are examples of hadrons.

As you remember, we learned about the existence of huge variety of particles when trying to look inside a nucleon, more particularly, the neutron. So, what the neutron is made of? Can we get the answer at last, after learning about the quarks? Yes, we can.

According to modern theories, all hadrons are composed of quarks. The quarks can be combined in groups of two or three. The bound states of two quarks are called *mesons*, and the bound complexes of three quarks are called *baryons*. No other numbers of quarks can form observable particles[1].

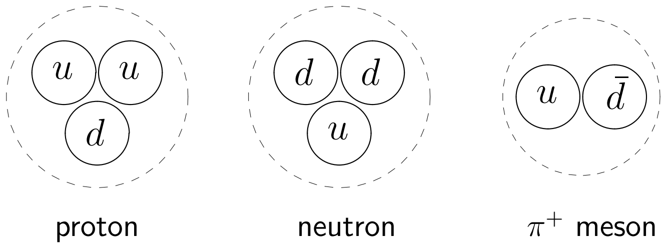


Figure 1.7: Quark content of the proton, neutron, and π^+-meson.

Nucleons are baryons and therefore consist of three quarks while the pion is a meson containing only two quarks, as schematically shown in Fig. 1.7. Comparing

[1]Recently, experimentalists and theoreticians started to actively discuss the possibility of the existence of *pentaquarks*, exotic particles that are bound complexes of five quarks.

this figure with Table 1.4, you can see why quarks have fractional charges. Counting the total charge of a hadron, you should not forget that anti-quarks have the opposite charges. The baryon number for an anti-quark also has the opposite sign (negative). This is why mesons actually consist of a quark and anti-quark in order to have total baryon number zero.

Particle reactions

At the early stages of the particle physics development, in order to find the constituent parts of various particles, experimentalists simply collided them and watched the "fragments". However, this straightforward approach led to confusion. For example, the reaction between the π^- meson and proton,

$$\pi^- + p \longrightarrow K^0 + \Lambda^0 \ , \tag{1.8}$$

would suggest (if naively interpreted) that either K^0 or Λ^0 is a constituent part of the nucleon while the pion is incorporated into the other "fragment". On the other hand, the same collision can knock out different "fragments" from the same proton. For example,

$$\pi^- + p \longrightarrow \pi^0 + n \ , \tag{1.9}$$

which leads to an absurd suggestion that neutron is a constituent part of proton.

The quark model explains all such "puzzles" nicely and logically. Similarly to chemical reactions that are just rearrangements of atoms, the particle reactions of the type (1.8) and (1.9) are just rearrangements of the quarks. The only difference is that, in contrast to chemistry where the number of atoms is not changing, the number of quarks before the collision is not necessarily equal to their number after the collision. This is because a quark from one colliding particle can annihilate with the corresponding antiquark from another particle. Moreover, if the collision is sufficiently powerful, the quark-antiquark pairs can be created from vacuum.

It is convenient to depict the particle transformations in the form of the so-called *quark flow diagrams*. On such diagrams, the quarks are represented by lines that may be visualized as the trajectories showing their movement from the left to the right.

For example, the diagram given in Fig. (1.8), shows the quark rearrangement for the reaction (1.8). As you can see, when the pion collides with proton, its $\bar{u}$ quark

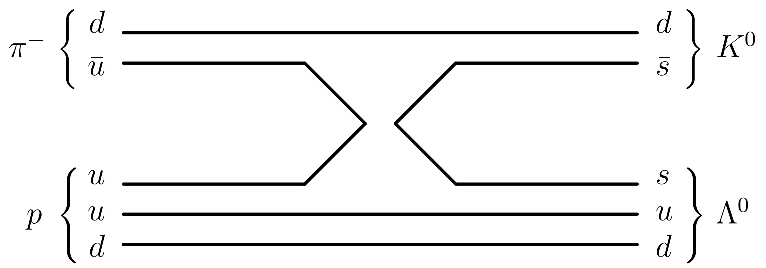


Figure 1.8: Quark-flow diagram for the reaction $\pi^- + p \longrightarrow K^0 + \Lambda^0$.

annihilates with the u quark from the proton. At the same time, the $s\bar{s}$ pair is created from the vacuum. Then, the $\bar{s}$ quark binds with the d quark to form the strange meson K^0, while the s quark goes together with the ud pair as the strange baryon Λ^0.

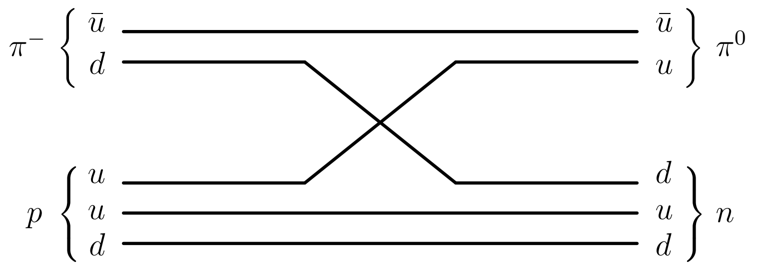


Figure 1.9: Quark-flow diagram for the reaction $\pi^- + p \longrightarrow \pi^0 + n$.

The charge-exchange reaction (1.9) is a more simple rearrangement process shown in Fig. 1.9. You may wonder why the quark and antiquark of the same flavor in the π^0 meson do not annihilate. Yes they do, but not immediately. And due to this annihilation, the lifetime of π^0 is 100 million times shorter than the lifetime of $\pi^\pm$ (see Table 1.3).

Despite its simplicity, the quark-flow diagram technique is very powerful method not only for explaining the observed reactions but also for predicting new reactions that have not yet been seen in experiments. Knowing the quark content of particles (which is available in modern Physics Handbooks), you can draw plenty of such diagrams that will describe possible particle transformations. The only rule is to keep the lines continuous. They can disappear or emerge only for a quark-antiquark pair of the same flavor.

However, the continuity of the quark lines is valid only for the processes caused by the strong interaction. Indeed, the β-decay of a free neutron (caused by the weak forces),

$$n \longrightarrow p + e^- + \bar{\nu}_e \ , \tag{1.10}$$

as well as the β-decay of the nuclei, indicate that quarks can change flavor. In particular, the β-decay (1.10) or (1.6) happens because the d quark transformes into the u quark,

$$d \longrightarrow u + e^- + \bar{\nu}_e \ , \tag{1.11}$$

due to the weak interaction, as shown in Fig. 1.10

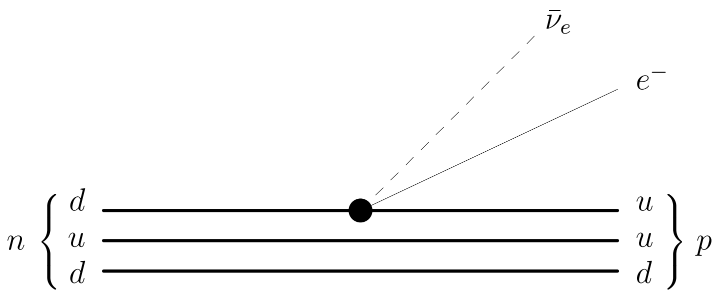


Figure 1.10: Quark-flow diagram for the β decay of neutron.

Quark confinement

At this point, it is very logical to ask if anybody observed an isolated quark. The answer is "no". Why? And how can one be so confident of the quark model when no one has ever seen an isolated quark?

Basically, you can't see an isolated quark because the quark-quark attractive force does not let them go. In contrast to all other systems, the attraction between quarks grows with the distance separating them. It is like a rubber cord connecting two balls. When the balls are close to each other, the cord is not stretched and the balls do not feel any force. If, however, you try to separate the balls, the cord pulls them back. The more you stretch the cord, the stronger the force becomes (according to the Hook's law of elasticity). Of course, a real rubber cord would eventually break. This does not happen with the quark-quark force. It can grow to infinity. This phenomenon is called the *confinement of quarks*.

Nonetheless, we are sure that the nucleon consists of three quarks having fractional charges. A hundred years ago Rutherford, by observing the scattering of charged particles from an atom, proved that its positive charge is concentrated in a small nucleus. Nowadays, similar experiments prove the existence of fractional point-like charges inside the nucleon.

The quark model actually is much more complicated than the quark-flow diagrams. It is a consistent mathematical theory that explains a vast variety of experimental data. This is why nobody doubts that it reflects the reality.

1.9.4 Forces of nature

If asked how many types of forces exist, many people start counting on their fingers, and when the count exceeds ten, they answer "plenty of". Indeed, there are gravitational forces , electrical, magnetic, elastic, frictional forces, and also forces of wind, of expanding steam, of contracting muscles, etc.

If, however, we analyze the root causes of all these forces, we can reduce their number to just a few fundamental forces (or *fundamental interactions*, as physicists say).

For example, the elastic force of a stretched rubber cord is due to the attraction between the molecules that the rubber is made of. Looking deeper, we find that the molecules attract each other because of the electromagnetic attraction between the electrons of one molecule and nuclei of the other. Similarly, if we depress a piece of rubber, it resists because the molecules refuse to approach each other too close due to the electric repulsion of the nuclei. Therefore the elasticity of rubber has the electromagnetic origin.

Any other force in the human world can be analyzed in the same manner. After doing this, we will find that all forces that we see around us (in the macroworld), are either of gravitational or electromagnetic nature. As we also know, in the microworld there are two other types of forces: The strong (nuclear) forces that act between all hadrons, and the weak forces that are responsible for changing the quark flavors.

Therefore, all interactions in the Universe are governed by only four fundamental forces: Strong, electromagnetic, weak and gravitational. These forces are very different in strength and range. Their relative strengths are given in Table 1.5. The most strong is the nuclear interaction. The strength of the electromagnetic forces is one hundred times lower. The weak forces are nine orders of magnitude weaker than the nuclear forces, and the gravity is 38 orders of magnitude weaker! It is amazing that this subtle interaction governs the cosmic processes. The reason is that the gravitational forces are of long range and always attractive. There is no such thing as negative mass that would screen the gravitational field, like negative electrons screen the field of positive nuclei.

Force	Relative Strength	Range
Strong	1	Short
Electromagnetic	0.0073	Long
Weak	10^{-9}	Very Short
Gravitational	10^{-38}	Long

Table 1.5: Four fundamental forces and their relative strengths.

Towards the unified force

Physicists always try to simplify things. Since there are only four fundamental forces, it is tempting to ask "If only four, then why not only one?". Can it be that all interactions are just different faces of one master force?

The first who started the quest for unification of forces was Einstein. After completing his general theory of relativity, he spent 30 years in unsuccessful attempts to unify the electromagnetic and gravity forces. At that time, it seemed logical because both of them were infinite in range and obeyed the same inverse square law. Einstein failed because the unification should be done on the basis of quantum laws, but he tried to do it using the classical concepts.

Electro-weak unification

Now it is known that despite the similarities in form of the gravity and electromagnetic forces, the gravity will be the last to yield to unification. The more implausible unification of the electromagnetic and weak forces turned out to be the first successful step towards the unified interaction.

In 1979, the Nobel prize was awarded to Weinberg, Salam, and Glashow, who developed a unified theory of electromagnetic and weak interactions. According to that theory, the electromagnetic and weak forces converge to one *electro-weak* interaction at very high collision energies. The theory also predicted the existence of heavy particles, the W and Z, with masses around 80000 MeV and 90000 MeV, respectively. These particles were discovered in 1983, which brought experimental verification to the new theory.

Grand unification

The next step was to try to combine the electro-weak theory with the theory of the strong interactions (i.e. quark theory) in a single theory. This work was called the *grand unification*. Currently, physicists discuss versions of such theory that predicts the convergence of the three forces at awfully high energies $\sim 10^{17}$ MeV. The quarks and leptons in this theory, are the unified *leptoquarks*.

The grand unification is not that successful as the electro-weak theory. It has the problem of mathematical consistency and contradicts to at least one experiment. The matter is that it predicts the proton decay,

$$p \longrightarrow e^+ + \pi^0 \ ,$$

that does not conserve both the baryon and lepton numbers, with the lifetime of $\sim 10^{29}$ years. The measurements show, however, that the lifetime of the proton is at least 10^{32} years.

Theory of everything

Some people believe that the grand unification has an inherent principal flaw. According to them, one cannot unify the forces step by step (leaving the gravity out), and the correct way is to combine all four forces in the so-called *theory of everything*.

There are few different approaches to unifying everything. One of them suggests that all fundamental particles (quarks and leptons) are just vibrating modes of string loops in multidimensional space. The electron is a string vibrating one way, the up-quark is a string vibrating another way, and so on. The other approach introduces a new level of fundamental particles, the *preons*, that could be constituent parts of quarks and leptons. The quest goes on.

Everyone agrees that constructing the theory of everything would in no way mean that biology, geology, chemistry, or even physics had been solved. The universe is so rich and complex that the discovery of the fundamental theory would not mean the end of science. The ultimate theory of everything would provide an unshakable pillar of coherence forever assuring us that the universe is a comprehensible place.

1.10 Origin of the universe

Looking deep inside microscopic particles, physicists need to collide them with high kinetic energies. The smaller parts of matter they want to observe, the higher energy they need. This is why they build more and more powerful accelerators. However, the accelerators have natural limitations. Indeed, an accelerator cannot be bigger than the size of our planet. And even if we manage to build a circular accelerator around the whole earth (along the equator, for example), it would not be able to reach the energy of $\sim 10^{17}\,\mathrm{MeV}$ at which the grand unification of fundamental interactions takes place.

So, what are we to do? How can we test the theory of everything? Is it possible at all? Yes, it is! The astronomically high values, like $\sim 10^{17}\,\mathrm{MeV}$, should be looked for in the cosmos, of course. Our journey towards extremely small objects eventually leads us to extremely large objects, like whole universe.

Equations of Einstein's theory of relativity can describe the evolution of the universe. Physicists solved these equations back in time and found that the universe had its beginning. Approximately 15 billion years ago, it started from a zero size point that exploded and rapidly expanded to the present tremendous scale. At the first instants after the explosion, the matter was at such incredibly high density and temperature that all particles had kinetic energies even higher than the unification energy $\sim 10^{17}$ MeV. This means that at the very beginning there was only one sigle force and no difference among fundamental particles. Everything was unified and "simple".

You may ask "So what? How can so distant past help us?". In many ways! The development of the universe was governed by the fundamental forces. If our theories about them are correct, we should be able to reproduce (with calculations) how that development proceeded step by step. During the expansion, all the nuclei and atoms in the cosmos were created. The amounts of different nuclei are not the same. Why? Their relative abundances were determined by the processes in the first moments after the explosion. Thus, comparing what follows from the theories with the observed abundances of chemical elements, we can judge validity of our theories.

Nowadays, the most popular theory, describing the history of the universe, is the so–called *Big-Bang* model. The diagram given in Fig. 1.11, shows the sequence of events which led to the creation of matter in its present form.

Nobody knows what was before the Big Bang and why it happened, but it is assumed that just after this enigmatic cataclysm, the universe was so dense and hot that all four forces of nature (strong, electromagnetic, weak, and gravitational) were indistinguishable and therefore gravity was governed by quantum laws, like the other three types of interactions. A complete theory of quantum gravity has not been constructed yet, and this very first "epoch" of our history remains as enigmatic as the Big Bang itself.

The ideal "democracy" (equality) among the forces lasted only a small fraction of a second. By the time $t \sim 10^{-43}$ sec the universe cooled down to $\sim 10^{32}$ K and the gravity separated. The other three forces, however, remained unified into one universal interaction mediated by an extremely heavy particle, the so-called X boson, which could transform leptons into quarks and vice versa.

When at $t \sim 10^{-35}$ sec most of the X bosons decayed, the quarks combined in trios and pairs to form nucleons, mesons, and other hadrons. The only symmetry which lasted up to $\sim 10^{-10}$ sec, was between the electromagnetic and weak forces

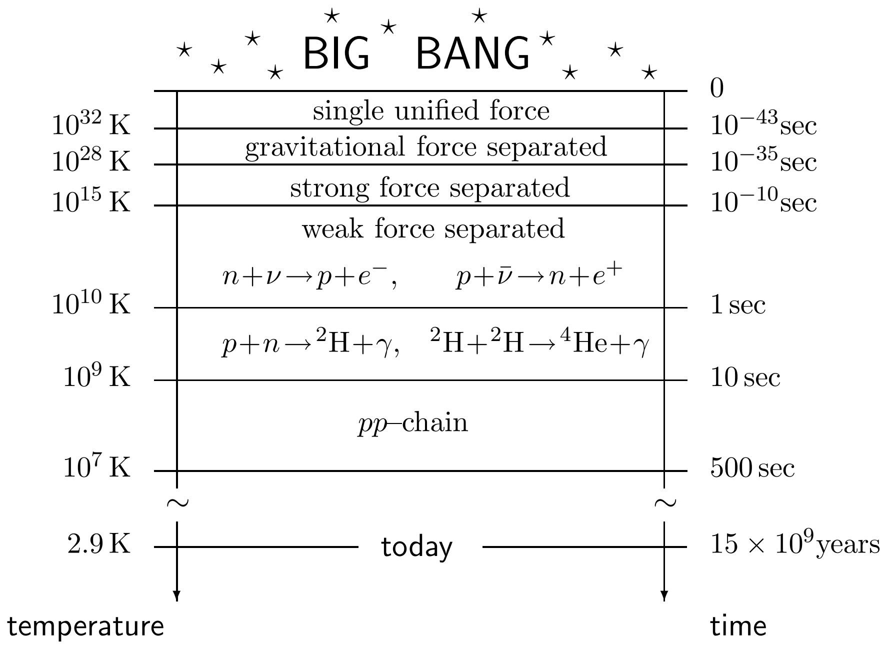


Figure 1.11: Schematic "history" of the universe.

mediated by the Z and W particles. From the moment when this last symmetry was broken ($\sim 10^{-10}$ sec) until the universe was about one second old, neutrinos played the most significant role by mediating the neutron-proton transmutations and therefore fixing their balance (neutron to proton ratio).

Already in a few seconds after the Big Bang nuclear reactions started to occur. The protons and neutrons combined very rapidly to form deuterium and then helium. During the very first seconds there were too many very energetic photons around which destroyed these nuclei immediately after their formation. Very soon, however, the continuing expansion of the universe changed the conditions in favour of these newly born nuclei. The density decreased and the photons could not destroy them that fast anymore.

During a short period of cosmic history, between about 10 and 500 seconds, the entire universe behaved as a giant nuclear fusion reactor burning hydrogen. This burning took place via a chain of nuclear reactions, which is called the *pp-chain* because the first reaction in this sequence is the proton-proton collision leading to the formation of a deuteron. Nowadays, the same *pp*-chain is the main source of energy in our sun and other stars.

But how do we know that the scenario was like this? In other words, how can we check the Big–Bang theory? Is it possible to prove something which happened 15 billion years ago and in such a short time? Yes, it is! The *pp*-chain fusion,

pp-chain:

$$\boxed{\begin{aligned} \mathrm{p}+\mathrm{p} &\rightarrow {}^{2}\mathrm{H}+\mathrm{e}^{+}+\nu_e \\ \mathrm{e}^{-}+\mathrm{p}+\mathrm{p} &\rightarrow {}^{2}\mathrm{H}+\nu_e \\ \mathrm{p}+{}^{2}\mathrm{H} &\rightarrow {}^{3}\mathrm{He}+\gamma \\ {}^{3}\mathrm{He}+{}^{3}\mathrm{He} &\rightarrow {}^{4}\mathrm{He}+\mathrm{p}+\mathrm{p} \\ {}^{3}\mathrm{He}+{}^{4}\mathrm{He} &\rightarrow {}^{7}\mathrm{Be}+\gamma \end{aligned}}$$

$$\boxed{\begin{aligned} \mathrm{e}^{-}+{}^{7}\mathrm{Be} &\rightarrow {}^{7}\mathrm{Li}+\nu_e \\ \mathrm{p}+{}^{7}\mathrm{Li} &\rightarrow {}^{8}\mathrm{Be}+\gamma \\ {}^{8}\mathrm{Be} &\rightarrow {}^{4}\mathrm{He}+{}^{4}\mathrm{He} \end{aligned}} \qquad \boxed{\begin{aligned} \mathrm{p}+{}^{7}\mathrm{Be} &\rightarrow {}^{8}\mathrm{B}+\gamma \\ {}^{8}\mathrm{B} &\rightarrow {}^{8}\mathrm{Be}^{*}+\mathrm{e}^{+}+\nu_e \\ {}^{8}\mathrm{Be}^{*} &\rightarrow {}^{4}\mathrm{He}+{}^{4}\mathrm{He} \end{aligned}}$$

is the key for such a proof.

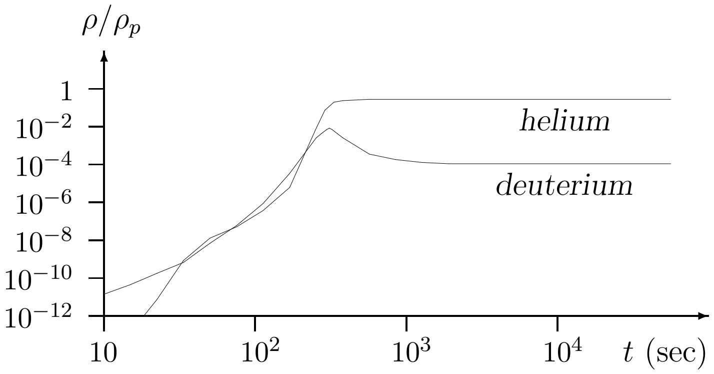


Figure 1.12: Mass fractions ρ (relative to hydrogen ρ_p) of primordial deuterium and ^{4}He versus the time elapsed since the Big Bang.

As soon as the nucleosynthesis started, the amount of deuterons, helium isotopes, and other light nuclei started to increase. This is shown in Fig. 1.12 for ^{2}H and ^{4}He. The temperature and the density, however, continued to decrease. After a few minutes the temperature dropped to such a level that the fusion practically stopped because the kinetic energy of the nuclei was not sufficient to overcome the electric repulsion between nuclei anymore. Therefore the abundances of light elements in the cosmos were fixed (we call them the *primordial abundances*). Since then, they practically remain unchanged, like a photograph of the past events, and astronomers can measure them. Comparing the measurements with the predictions of the theory, we can check whether our assumptions about the first seconds of the universe are correct or not.

Astronomy and the physics of microworld come to the same point from different directions. The Big Bang theory is only one example of their common interest. Another example is related to the mass of neutrino. When Pauli suggested this tiny particle to explain the nuclear β-decay, it was considered as massless, like the photon. However, the experiments conducted recently, indicate that neutrinos may have small non-zero masses of just a few eV.

In the world of elementary particles, this is extremely small mass, but it makes a huge difference in the cosmos. The universe continues to expand despite the fact that the gravitational forces pull everything back to each other. The estimates show, that the visible mass of all galaxies is not sufficient to stop and reverse the expansion. The universe is filled with a tremendous number of neutrinos. Even with few eV per neutrino, this amounts to a huge total mass of them, which is invisible but could reverse the expansion.

Thus, the cooperation of astronomers and particle physicists has led to significant advances in our understanding of the universe and its evolution. The quest goes on. A famous German philosopher Friedrich Nietzsche once said that "The most incomprehensible thing about this Universe is that it is comprehensible."