PARTICLES AND FIELDS

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Summary

The concept of atoms has contributed greatly to the development of physics. Each element has its own atom. Atoms can bind together to form molecules or molecules can dissociate into atoms in chemical reactions, in which the identity of each atom is kept. Thus, it was thought that the atom is indivisible smallest unit of the element. The concept of atoms was well established through the study of the laws of chemical reactions and the kinetic theory of gases based upon the existence of atoms.

First direct evidence for the existence of atoms came from study of Brownian motion and today we can even observe a single atom under appropriate conditions. It turned out

that atoms can be dissociated into its constituents by bombarding them by energetic particles and the structures of atoms became known to us. Now we know that atoms are no more indivisible. Atoms consist of electrons and a nucleus, a nucleus consists of protons and neutrons, and protons and neutrons consist of quarks. The hierarchy of these elementary constituents of matter is discussed.

The concept of field was introduced by Faraday. In modern physics every force is associated with its field. When the wave of an electromagnetic field interacts with a microscopic object such as an atom or an electron, it behaves as a train of microscopic particles called photons. The same applies to other force fields. Thus, even the force field has a particle nature with it.

The study of quantum physics is indispensable for understanding the microscopic world. By employing the basic ingredients of quantum physics, structures of atoms, molecules, and nuclei are discussed. The uncertainty and discrete nature of the microscopic world is at the heart of quantum physics, which leads to correct understanding of structures of atoms, molecules and nuclei.

At present, the most fundamental constituents of matter are quarks and leptons, all being point-like particle. The attributes and the classification schemes of these particles are presented. Ordinary matter consists of a few of these particles and others are unstable and decay into those which compose ordinary matter. There are many peculiarities about quarks and leptons, one of them being that no isolated quark exists in nature. Some of these peculiarities are discussed.

The fundamental forces acting between the elementary particles are classified into four forces: the gravitational force, strong force, electromagnetic force and weak force. All known forces in nature including frictional forces can be derived from these fundamental forces.

These forces are of a kind called the gauge interaction which comes from the gauge symmetry of the interacting matter and fields. This made possible to unify the electromagnetic and weak forces into a unified force and further unification schemes of all the four forces are being searched for. The quanta associated with the four force fields are gravitons, gluons, photons and weak bosons, all of them were identified experimentally except gravitons.

Introduction

Feynman (1918-1988), an eminent physicist of the late 20th century, once expressed an opinion that he will regard the concept of atoms as the most important concept in physics, if he were asked to choose a single concept which contributed most to the development of modern physics.

The ancient Greeks speculated about almost everything. Atomic view of matter could be traced back to the ancient Greek era. For example, Democritus (460-375 BC) speculated that our universe consists of atoms which cannot be divided further into smaller pieces and of an empty space. His ideas had been succeeded by Epikouros (342-271 BC) and much later by Lucretius (94-55 BC). A poem of Lucretius, “De rerum natura”, gave a poetic description of the ancient atomic views.

The speculations of Democritus and his followers, whose philosophy was based on atomism, were not generally accepted views of matter during the Middle Ages. The prevailing concepts of matter were those of Aristotle (384-322 BC) and of people of the Stoic school, who thought that space and matter were continuous and that all matter was one primordial stuff that was the habitat of four elementary principles – hotness, coldness, dryness, and wetness. The experimental evidence needed for evaluating the conflicting speculations about the constitution of matter became available much later only through the development of quantitative chemistry started in the last half of the 18th century.

The word “atom” originated from the Greek word “atmos”, which means an object indivisible any more. Since the last half of the 18th century, various experimental facts supporting existence of atoms have accumulated. At present we can even observe a single atom under an appropriate condition, so that there is no question about existence of atoms now. Also extensive efforts have been made to understand various physical phenomena based on the atomic view with great success.

In modern physics we know that an atom consists of a nucleus and electrons, and a nucleus itself consists of protons and neutrons. Furthermore, even protons and neutrons are composite particles which consist of particles called quarks. Atoms are no longer regarded as indivisible and the really elementary particles constituting matter are not atoms but instead quarks and leptons (The electron is one kind of leptons as we will see later). In Fig.1, we show a schematic illustration of the constitution of matter. If we regard quarks and leptons as atoms in the present days, the atomic views still hold in a somewhat revised manner.

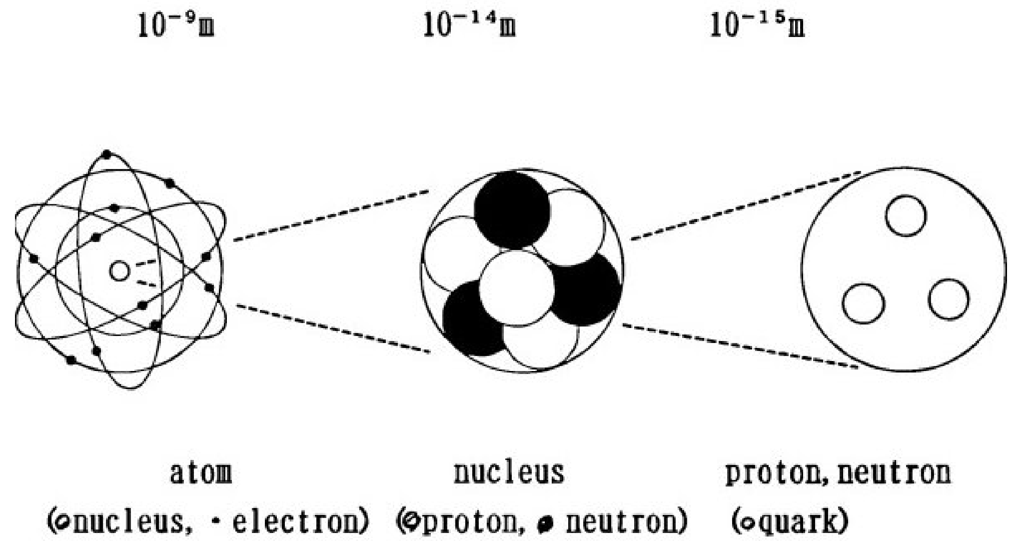

Figure 1. Constitution of matter

Suppose we try to divide a homogeneous substance such as iron or water. We know as facts of experience that each segment obtained through the division shares the same physical properties with the whole. If we continue dividing the substance to see whether the properties of a segment would finally differ from those of the whole, the logical outcome is either we can continue the dividing process for ever without seeing any change in its physical properties, or we find the size limit of segment such that the physical properties of smaller segments than the limiting size are no more those of the whole.

The former case corresponds to the continuum theory of matter and the latter case to the atomic theory of matter. We know now that any substance consists of atoms and molecules, which are the smallest unit of substance to share the physical properties of the substance. For example, an iron atom is the smallest unit of iron and a water molecule is the smallest unit of water. Although iron is a pure substance, water is a chemical compound made up of hydrogen and oxygen. If we divide a water molecule further, it will dissociate into hydrogen and oxygen atoms with no more properties of water.

There are varieties of pure substances in nature. Therefore, we expect there exists different kinds of atom, each corresponding to each of pure substances. Some ancient Greek philosophers endowed atoms with symmetric geometrical shapes such as a sphere or regular polyhedrons shown in Fig.2. They even speculated that beauty of natural formations originates from the symmetric properties of atom. Of course, no such detailed speculations had any relevance to the later evolution of physics.

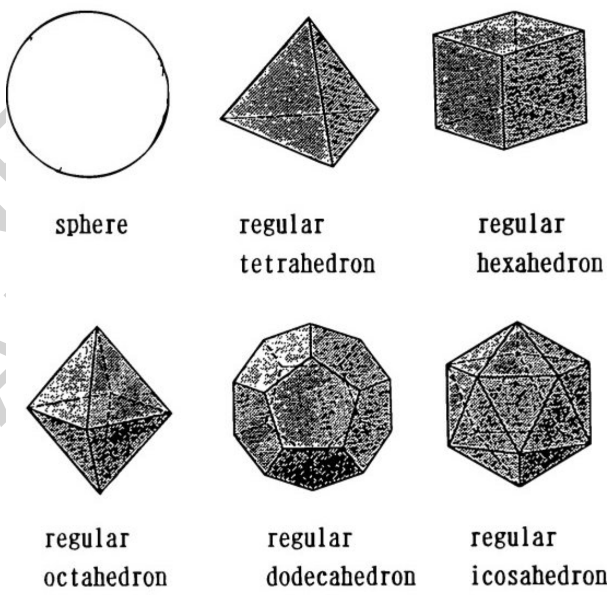

Figure 2. A sphere and regular polyhedrons

It was Lavoisier (1743-1794) who evolved the present concept of a chemical element which corresponds to pure substance. Water is a chemical compound and can dissociate into hydrogen and oxygen. Likewise, most substances are chemical compounds which consist of several different chemical elements. A chemical element is a substance which does not dissociate into different substances. The number of different chemical elements is limited and we know that 92 different elements exist in nature. Besides, we can artificially produce new elements, thus the total number of different elements is more than a hundred at present.

The person who contributed most to the foundation of the modern atomic theory of matter is Dalton (1766-1844). In 1799 Proust found the law of definite or constant proportions, which states that in every sample of any compound substance, formed or decomposed, the proportions in weight of the constituent elements are always the same. Dalton explained the law based on the atomistic view.

For example, water is formed from oxygen and hydrogen. When we combine oxygen of 8 grams and hydrogen of 1 gram, we obtain water of 9 grams with no residual oxygen or hydrogen remained. If we have hydrogen of 2 grams at the beginning, we obtain water of 9 grams with hydrogen of 1 gram remained. The proportions in weight of oxygen and hydrogen are always equal to 8 to 1, when they are combined into water. Dalton even assumed that a water molecule is formed by combining a single oxygen atom and a single hydrogen atom together. This assumption turned out to be wrong as we shall see later.

If the atom of each element has a definite mass and the proportions in number of the atoms combined into a compound substance are fixed, then we naturally expect that the proportions in weight of the constituent elements are always the same, thus explaining the law of definite proportions based on the atomic view.

Furthermore, Dalton proposed the law of multiple proportions in 1804. The law states that if substance A combines with substance B in two or more ways, forming substance C and D, then if the mass of A is held constant, the masses of B in the various products will be related in proportions which are the ratios of small integers.

For example, let us consider chemical compounds formed by nitrogen and oxygen. By employing the chemical symbols, we can denote some of these compounds as N_2O, NO, N_2O_3, where N and O denote a nitrogen atom and an oxygen atom respectively and N_2 and O_3 mean two nitrogen atoms and three oxygen atoms. These compounds are known to exist. For the fixed mass of nitrogen, the masses of oxygen in the three compounds are in proportions of 1 : 2 : 3 confirming the law of multiple proportions. The only plausible interpretation of the law is that when elements combine into chemical compounds they do so as discrete entities or atoms as was assumed by Dalton.

Another important law pertaining to volumes of gases was found by Gay-Lussac in 1808. Gay-Lussac's law states that if gas A combines with gas B to form gas C, all at the same pressure and temperature, then the ratios of the volumes of A, B, and C will all be ratios of simple integers. When a chemical compound is formed through some chemical reactions of two kinds of gases, these gases combine in a definite ratio of volumes.

For example, if we combine hydrogen gas of 2 liters with oxygen gas of 1 liter, water vapor of 2 liters is formed without any hydrogen or oxygen gas remained. Of course,

volume of gas depends on pressure, and volume will increase with decreasing pressure. The ratio of volumes is one obtained when the gases are under the same pressure. Volume of gas depends also on temperature and it increases with increasing temperature. Therefore, we must measure volumes of gases at the same pressure and temperature. If we mix hydrogen gas of 3 liters instead of 2 liters with oxygen gas of 1 liter, we obtain water vapor of 2 liters with hydrogen gas of 1 liter remained. Gay-Lussac's law were tested for many chemical reactions of gases and well confirmed to be valid.
In 1811, Avogadro proposed a hypothesis called Avogadro's law, which states that at the same pressure and temperature equal volumes of all gases contain the same number of molecules. If we apply this hypothesis to the chemical reaction of forming water vapor out of oxygen and hydrogen gases, we find that two hydrogen molecules and one oxygen molecule combine and form two water molecules. Thus, Gay-Lussac's law can be interpreted as the result of atoms of different elements combine into molecules of chemical compounds with ratios in number of the atoms equal to ratios of simple integers.

Since the ratio in mass of the hydrogen and oxygen gases is 1 to 8 and the ratio in number of the hydrogen and oxygen molecules is 2 to 1 when they combine into water, the ratio in weight of a hydrogen molecule and an oxygen molecule equals to 1 to 16. If we denote the mass of a hydrogen molecule by m, the mass of an oxygen molecule is $16m$. Since two hydrogen molecules and one oxygen molecule combine and form two water molecules, the mass of a water molecule is $9m$.

Now let us assume that the hydrogen and oxygen molecules are the smallest units which cannot be divided further. In order to form two water molecules out of two hydrogen and one oxygen molecules, each one of the hydrogen molecules might become the constituent of each of the water molecules. But there is no way to supply oxygen to two water molecules unless the oxygen molecule can be split into two. Then Avogadro speculated that both oxygen and hydrogen molecules are divisible and they consist of two oxygen atoms and two hydrogen atoms respectively. Thus, a water molecule consists of a hydrogen molecule and an oxygen atom, i.e., two hydrogen atoms and one oxygen atom. Dalton's ssumption of a water molecule being composed of a hydrogen atom and an oxygen atom was wrong and replaced by Avogadro's assertion.

In Fig.3 we illustrate how water vapor will be formed out of oxygen and hydrogen gases based on the atomic view. If we use chemical symbols, the reaction can be written as

$$2H_2 + O_2 \Rightarrow 2H_2O$$

As we can see from the above equation, the number of hydrogen atoms and that of oxygen atoms are conserved in the reaction. In chemical reaction atoms can change their partners to be combined, but do not lose their identities.

Making use of Avogadro's hypothesis, similar analysis based on the atomic view was made on various chemical reactions where hydrogen or oxygen gases are involved. The results of the analysis were consistent with the assumption that an oxygen molecule consists of two oxygen atoms and a hydrogen molecule consists of two hydrogen atoms.

Like hydrogen and oxygen, for some of pure elements the smallest unit of matter in gaseous state is not an atom but a molecule which consists of two identical atoms. These molecules can be split into atoms when the gas is involved in some chemical reactions. This means that we have to differentiate molecules from atoms even for some of pure elements. Of course, there are other elements such as helium where the smallest unit is a single atom.

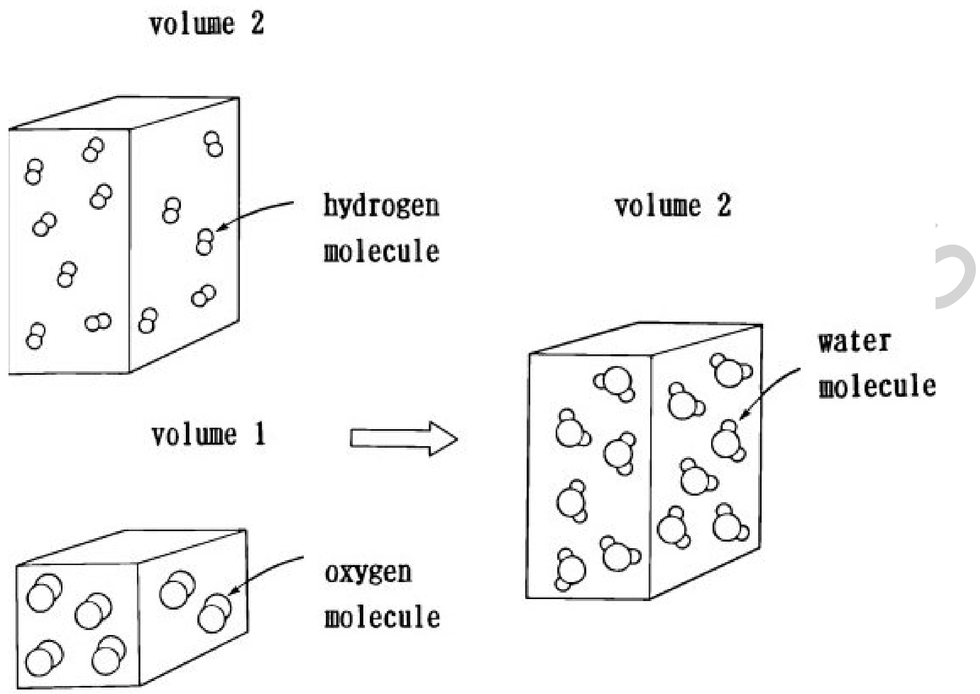

Figure 3. $2H_2 + O_2 \Rightarrow 2H_2O$ (H –oxygen atom, O-hydrogen atom)

As we have described how to interpret various laws of chemical reactions, we need existence of discrete entities, namely, atoms and molecules. The fact that the atomic view provided us a simple, unified and consistent explanation for various laws such as the law of definite proportions, the law of multiple proportions and Gay-Lussac's law were regarded as a strong support or evidence for existence of atoms and molecules. Thus, by the middle of the 19th century, most scientists had become to accept the atomic view as a correct view to interpret chemical reactions as well as laws of chemical reactions. However, since no one had ever observed atoms directly and evidences for existence of atoms were indirect ones at best, there were still quite a few scientists who were against or skeptical about the existence of atoms.

We might add some comments on quantitative study of chemical reactions which led to the atomic view of the nature of matter. Although the above descriptions of chemical reactions might have given readers an impression that a unified atomic view was easily obtained through an analysis of various chemical reactions but that is not the case in reality. In most experiments there were rather large experimental errors associated with the methods used or technical precisions available at the time. Also there existed rather large statistical errors associated with the limited amount of data available.

If we look at experimental data at the time, there were many which contradict the correct data available now. For example, the atomic or molecular masses of a particular element obtained through analysis of different chemical reactions did not always coincide and in some cases they even contradicted each other. Also some working hypothesis turned out to be wrong and had to be altered later, as was the case of Dalton's hypothesis which failed to make distinction between atoms and molecules. Furthermore, it was not easy to identify pure elements and even Lavoisier misstated some of chemical compounds as pure elements.

There are always unavoidable limits in accurately proving physical laws and concepts only through experiments and observations. So we cannot underestimate important roles played by scientist's faith that the constitution of matter should be simple, which had certainly helped them to establish the atomic view of matter.

The number of molecules in a mole of a gas is called Avogadro's number or the Avogadro constant, which we denote by N_A. In order to determine N_A, people had to wait until they could estimate masses of molecules. The present value of the Avogadro constant is about

$$N_A = 6.022 \times 10^{23} \quad \text{molecules per mole} \tag{1}$$

A mole of a gas is defined as follows. We define a mole of carbon as the amount of carbon in 12 grams of the substance. The relative molecular and atomic masses are all dimensionless ratios. The atomic mass of carbon is arbitrarily set at exactly equal to 12 as the standard and other atomic and molecular masses are defined relative to this standard mass. One mole of a gas is the amount of the gas in its molecular mass of the substance. The volume V_0 of a mole of a gas at a pressure of 1 standard atmosphere and a temperature of 0°C is about

$$V_0 = 2.241 \times 10^{-2}\,\mathrm{m}^3 \quad \text{per mole} \tag{2}$$

Another kind of evidence for the atomic view of matter came from success of the kinetic theory of gases which we already described in the previous chapters (see *Development of Fundamentals in Physics – Thermodynamics and Heat transfer and Physical Systems and Laws – Statistical Physics*). Let us consider a gas contained in a box. If we assume that a gas consists of a huge number of molecules moving more or less freely in the box, we could infer that the temperature of the gas is related to the average kinetic energy of the molecules and the pressure of the gas is related to the average force exerted by the molecules upon the walls of the box through collisions between the molecules and the walls. Not only the kinetic theory of gases provided us deeper insight into what temperature and pressure are, but also it was able to derive equations of state such as the law of ideal gases, which explained even quantitatively various thermal properties of gases.

When we listen to a weather report of a radio or television broadcasting, atmospheric temperatures of various districts and variations of atmospheric pressures are reported every day. This means that we can infer the state of atmospheric air only through knowledge of a few macroscopic quantities such as pressure and temperature. Although we cannot feel or know motion of individual molecules, it is gratifying that any system in thermal equilibrium can be described by a few macroscopic quantities which are related to the averages of appropriate properties of microscopic constituents.

The kinetic theory of gases developed and founded by Maxwell and Boltzmann from 1860s to 1870s explained nicely pressure and temperature of gases based on the atomic view and the theory was able to derive various laws such as Boyle's law of gases, thus providing us a bridge to connect macroscopic descriptions of matter with its microscopic descriptions. In spite of the success of the kinetic theory of gases and of the success of the molecular theory of chemical reactions, it had taken a long time before the atomic nature of matter was accepted by most scientists. This was similar to the gradual acceptance of the Copernican model of our solar system.

Today everybody knows that the planets including the earth orbit the sun. However, the long lasting model of the solar system was the geocentric, or earth centered, model proposed by Hipparchus in the second century BC. The epicyclic theory of planetary motion worked out by Ptolemy three centuries after Hipparchus provided the first comprehensive model of the universe. His model, with its many epicycles and equants, was really quite complicated, but it provided a good match between the predictions of the model and the observations of the planets.

Copernicus's sun centered, or heliocentric, model described in his great book "On the Revolution of the Celestial Orbs" appeared in 1543, the year of his death. In spite of the great simplicity of the model and its successful predictions of the planetary motions, it took several decades before the model became generally accepted through the accurate observations of the planetary motions by Tycho Brahe and its interpretation by Kepler.

Very often, the same physical phenomena could be explained equally well by different models. Each of the models can be further elaborated to incorporate new information added. Thus it is not easy to resolve which one of the models is correct, although a simpler model might be of more universal nature and have a better chance to be the correct one. Planck, a founder of quantum physics, once stated that the resolution of the conflicting theories can be often made by the death of the opponents and the absence of their followers, which seems to be true also in the case of the victory of the atomic view of matter over the other views.

The first more or less direct evidence for the atomic view of matter was the Brownian motion found by Brown in 1827. Brown observed that the microscopic pollen grains suspended in water appeared to move around in random fashion as shown in Fig.4. Soon later it was found that any kind of fine particles suspended in a liquid performed such a random motion. Eventually, it was realized that the molecules of a liquid are in constant motion and that the suspended particles recoiled when hit by the molecules of the liquid.

In 1905 Einstein derived an equation that describes how a suspended particle should migrate in a random manner through a liquid, and then Perrin verified Einstein's formula through experiments. In order to fit the data with the theory, Perrin needed to give quantitative estimates of the mass of a molecule and of the Avogadro constant. The value of the constant obtained fits well to its present value. Through these works on Brownian motions, most scientists became convinced with the truth of the atomic theory of matter.

Modern Atomism

So far we have described how the atomic view of matter had gradually become accepted by people through the analysis of chemical reactions and the study of the kinetic theory of gases. The smallest unit of a gas is a molecule which consists of atoms. In the gaseous state molecules are far apart from one another and more or less freely moving without being much affected by the motions of other molecules. They may occasionally collide with one another, but collisions are not violent enough to dissolve molecules into atoms so that they keep their identities through collisions.

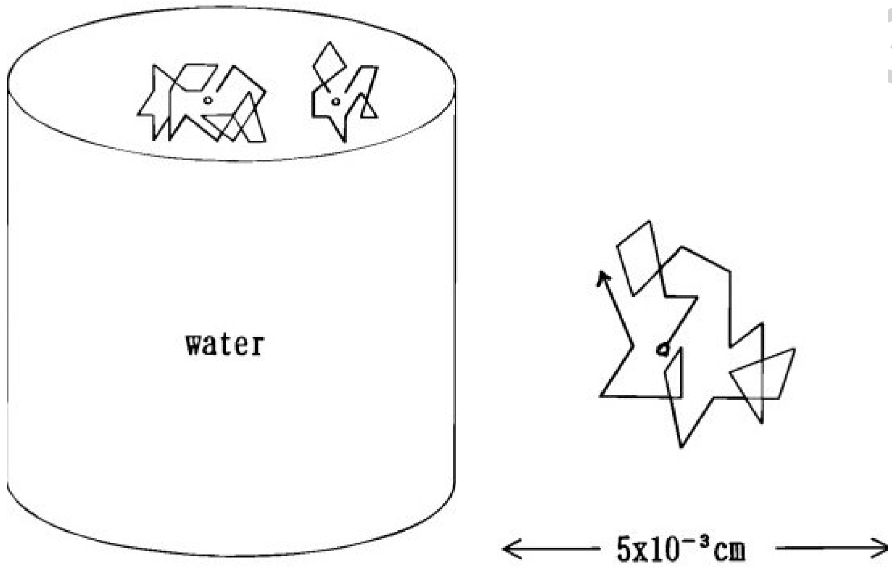

Figure 4. Brownian motion (o pollen grains). The figure on the right side shows the scale of Brownian motion

If we keep cooling a gas, it will become a liquid, and then a solid. In a liquid or a solid, average molecular distances become much shorter than those in a gas and they are even comparable to the size of the molecule. Since the matter is densely occupied by molecules in its liquid or solid phase, the matter cannot be considered any more as an aggregate of independent molecules. Instead, it would become more appropriate to regard atoms as the constituent units of matter. We show schematic views of the compositions of a gas, liquid, and solid in Fig.5.

In Fig.6 we show the crystalline structure of a certain substance taken by an electron microscope, which is a device to take a photo of microscopic structures of matter. At the left bottom corner we show an ordered array of atoms found through analysis of the photo, where small circles with different radii denote atoms of different elements. We can clearly see how atoms are arrayed in an ordered fashion in the crystalline structure of the substance.

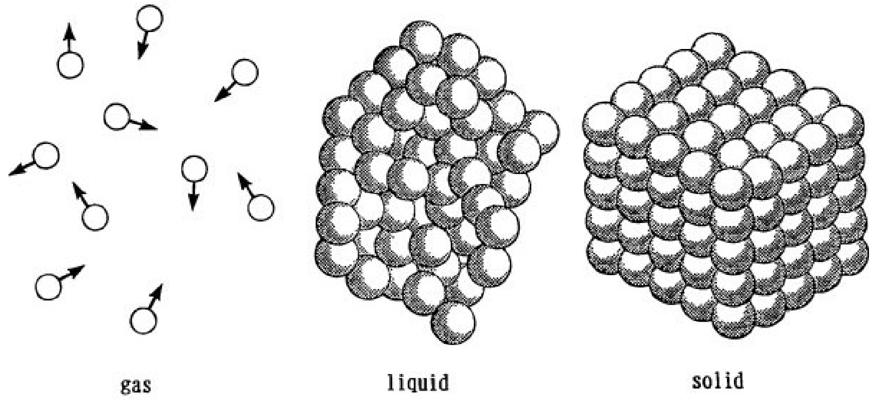

Figure 5. The organization of atoms in a gas, liquid, and solid

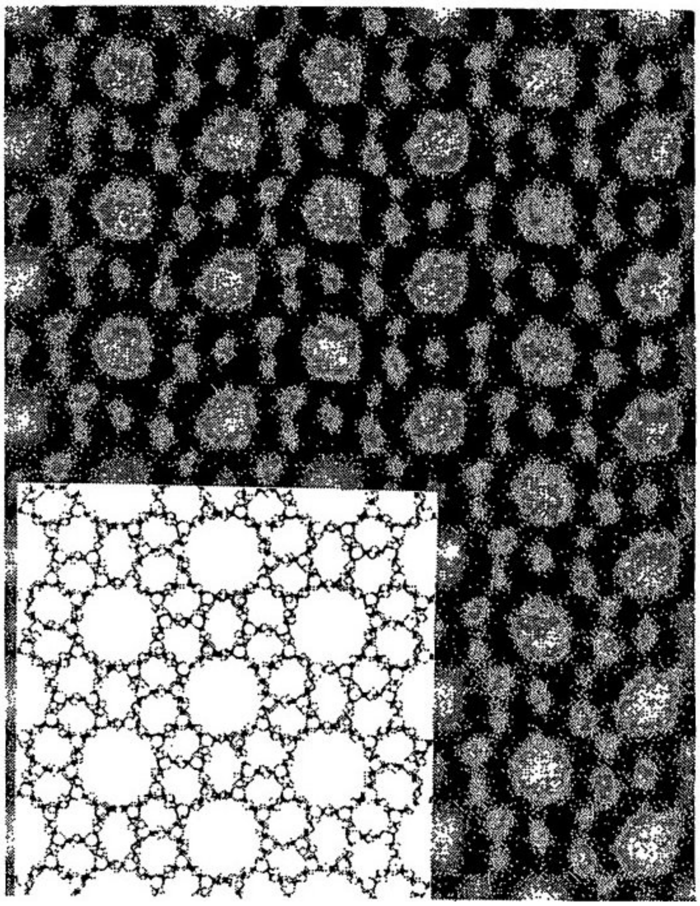

Figure 6. A crystalline structure showing the ordered array of atoms (Picture by O.Terasaki)

At the beginning of the 20^{th} century, the internal structure of atoms was still unknown. Today, we know that each atom contains a very tiny massive core called nucleus, which carries a positive charge and nearly all the mass of the atom. Also an atom has a number of negatively charged electrons each with charge $-e$, which orbit the nucleus located at the center of the atom. The number of electrons Z equals to the atomic number of the element in question. Since each atom is electrically neutral, the total charge $-Ze$ carried by the electrons is balanced by the positive charge Ze of the nucleus.

The number of electrons in an atom or, equivalently, the charge of the nucleus characterizes the element. Hydrogen is the lightest element and its atom possesses only one electron. Helium atoms possess two electrons and lithium atoms possess three electrons. The heaviest element found in nature is uranium and its atom possesses 92 electrons. Any element whose atoms carry electrons up to 92 are all found in nature and we can even artificially produce some elements which possess more than 92 electrons.

The structure of an atom is remarkably similar to the structure of our solar system. In Fig.7 we show the orbits of various planets of our solar system. If we substitute the sun by the nucleus and the planets by the electrons, we can well imagine the structure of an atom formed by electrons and a nucleus. Of course, the obvious difference exists between the two systems. The planets of our solar system are different in their sizes and masses from one another, but the electrons in atoms are all exactly identical.

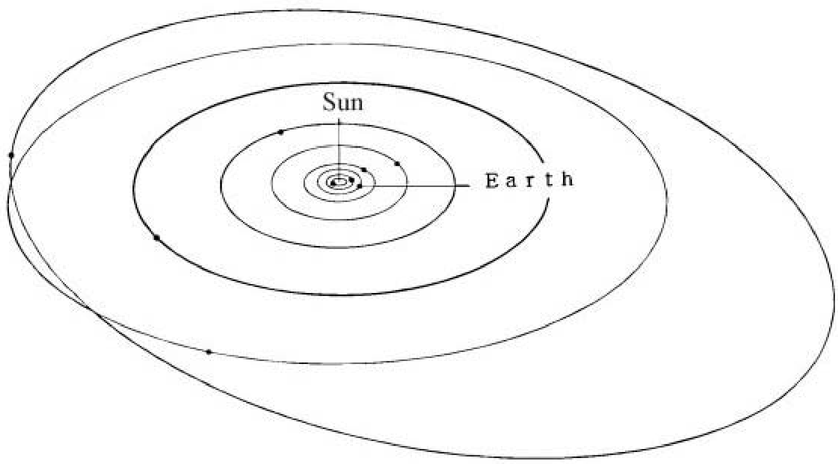

Figure 7. Our solar system (the plannets from inside : Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto)

Each planet of the solar system is acted by the gravitational force due to the sun and it orbits the sun along its elliptic orbit. Likewise, electrons in an atom are acted by the Coulomb force due to the positive charge of the nucleus and orbit the nucleus. The gravitational and Coulomb forces are both long distance forces and follow the same inverse square law, decreasing in their strengths in proportion to the inverse square of the distance. Therefore, if we can apply Newton's equation of motion to the motion of electrons in an atom, we expect that orbits of electrons in an atom are quite similar to those of planets in the solar system because of the similarity between the two forces.

The ratio of the radius of the sun to the size of the solar system is about 10^{-4}, while the ratio of the radius of the nucleus to that of the atom is about 10^{-5}. Like the solar system, an atom almost consists of an empty space where a tiny nucleus and tiny electrons are floating here and there. The speculation of Democritus that the universe consists of atoms and an empty space can also apply to a tiny universe, i.e., an atom. Atoms keep their own size and shape almost undisturbed even when they form a liquid or a solid where atoms are densely packed. Therefore, although a solid or liquid looks like a dense matter, it consists of an almost empty space contrary to our intuition.

As the sun carries nearly all the mass of the solar system, the mass of the nucleus accounts for almost all the mass of the atom. For a hydrogen atom the mass of its electron only accounts for 0.06% of the mass of the atom. We might add one more similarity. Every planet in the solar system turns on its own axis and likewise electrons in an atom turn on their own axes. Thus every constituent in both the systems is not only moving about the center of the system but also rotating about its own axis.

So far we have stressed on the similarities between the solar and atomic systems, and the similarities are really remarkable. On the other hand, there exist some basic differences between the two systems. First, the force to hold the planets in the solar system is the gravitational force, while the force to hold electrons and a nucleus in an atom is the Coulomb force. The planets and the sun are all electrically neutral to a good accuracy and we can safely neglect Coulomb forces between them. Electrons and nuclei are very tiny objects with extremely small masses and gravitational forces between them can be safely neglected.

Although the gravitational force is always attractive, the Coulomb force is attractive for a pair of particles with charges of opposite sign but is repulsive for a pair of particles with charges of same sign. Thus the planets in the solar system attract one another, while the electrons in an atom repel one another. This difference between the two systems is generally of minor importance, because the major force responsible to the formation of the system is the gravitational force between the sun and planets in the solar system and the Coulomb force between the electrons and the nucleus in the atomic system.

The most important difference between the two systems is the difference between the basic laws governing them. The solar system is a macroscopic system which can be well described by Newtonian mechanics, while the atomic system is a microscopic one which must be described by quantum mechanics.

In our universe there are a huge number of stars, and many of them are expected to have their own planets like the sun. But there would be no star which has the same number and same kinds of planets with our solar system. Also the orbits of planets of a star will differ from those of the planets in our solar system, because the orbits are determined by the initial conditions specified when the system was formed, Since each star has its own history from birth, the likelihood of finding a solar system exactly identical with our solar system should be infinitesimally small.

The basic characteristics of a quantum system such as an atomic system are uncertainty and discreteness of physical quantities of the system. Although we will discuss quantum systems and quantum mechanical laws in a later chapter (see *Quantum Systems*), we shall briefly discuss typical features of atomic systems due to the quantum nature of the systems.

The state of motion of an electron in an atom or in any closed system cannot change continuously, and the orbit of an electron must be one of the discrete orbits allowed by the quantum mechanical laws of motion. The number of the allowed orbits could be either finite or infinite, but they are apart from one another and the energy of an electron in an orbit also differs discretely from one to another. In Fig.8 we illustrate a schematic view of some allowed orbits for the electron in a hydrogen atom.

The electron in an orbit can spontaneously move into another orbit, but there is no way for the electron to change its orbit continuously from one to another. The energy of an electron or the energy of an atom changes discontinuously when the electron changes its orbit. Of course, the amount of discontinuity in energy is of a microscopic order and negligibly small in a macroscopic scale.

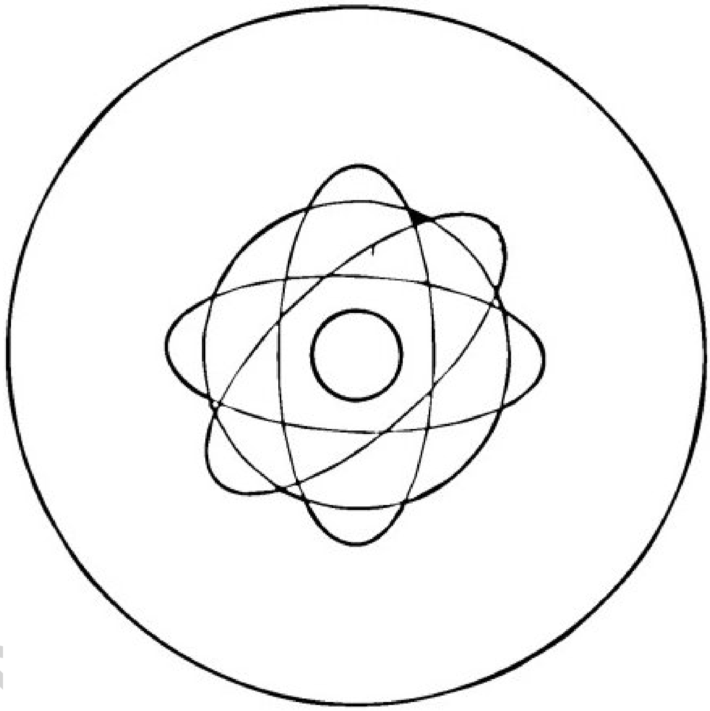

Figure 8. Some inner orbits for the electron in a hydrogen atom

The other eminent feature of the atomic system is the uncertainty of physical quantities. According to the uncertainty principle of Heisenberg, the position and velocity (or momentum) of an electron are subject to uncertainty and we can only predict the probability distributions of these physical quantities. Therefore, we cannot draw a line of an orbit as we did in Fig.8, because the position of an electron cannot be uniquely specified at any given time. The electron could be observed at other points away from the line of the orbit.

In Fig.9 we show the probability distributions of the position of the electron in a hydrogen atom for two different states of the electron. One of them corresponds to a circular orbit of the electron and the other to an elliptic orbit. Peaks in the distributions are places where the probability for finding the electron is large and valleys are places where the probability is small. The orbits in Fig.8 should be regarded as curves which connect continuously points on the peak of the distribution.

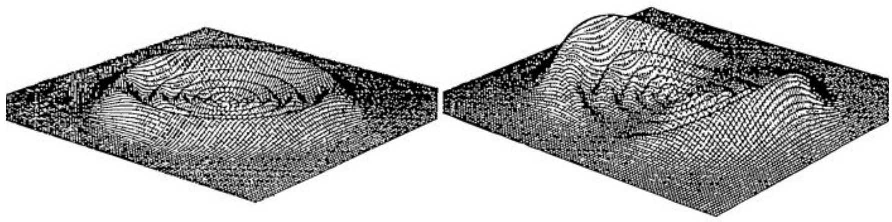

Figure 9. The probability distribution of the position of the electron in a hydrogen atom

An important fact about atoms is that the atoms of an element are all perfectly identical and indistinguishable from one another. This is really a remarkable fact, but, at the same time, this is what we expected. Otherwise, the success of the atomic theory would not be valid. If there exist atoms of different shapes and sizes for a given element, the atom cannot be qualified as the smallest unit of the element in question.

However, according to our common sense based on classical physics, if the atoms of an element have a certain shape of a finite size, we should be able to change their shape and size and even change them continuously. Therefore, it is not easy to understand why atoms of an element are all identical in their shape and size.

Only quantum physics can give clear answers for the fundamental questions such as the equality of atoms of an element. For simplicity, let us consider the hydrogen atom, which consists of an electron and a nucleus. In classical physics two mutually attracting bodies will finally stick together by losing the energy of their relative motion and they come to rest at the same position. So the electron in a hydrogen atom will fall into the nucleus.

In quantum physics an electron cannot be at rest at a fixed position. If the position and velocity (momentum) of the electron take fixed values at the same time, it is against the uncertainty principle of quantum mechanics. Since an electron cannot be at rest ($v = 0$) at the position of the nucleus, an orbit which is a little away from the nucleus becomes the most stable orbit allowed for the electron.

There are many possible atomic orbits of an electron which are allowed in quantum mechanics. These are discrete orbits separated discontinuously from one another. When the electron is in the orbit nearest to the nucleus, it will be most strongly attracted by the nucleus and, thus, most tightly bound to the nucleus. This state is called the ground state of the hydrogen atom, which has the lowests energy possible. It is important to notice that there is no way for the electron in the ground state to further lose its energy and thus the state is stable.

If the electron is in an orbit further away from the nucleus, the atom has a higher energy than the energy of the ground state. These states are called excited states of the hydrogen atom. The electron in an excited state can spontaneously move into another orbit nearer to the nucleus by lowering its energy through emission of radiations. In

Fig.10 we show how an electron in an excited state finally moves into the ground state through emission of radiations.

A hydrogen atom in any excited state will eventually falls into the ground state and will remain in that state unless enough energy is added from outside to the atom to excite the ground state into an excited one. Since the energy for the excitation is finite because of the discreteness of states, atoms will remain in their ground state under normal circumstances. This explains why atoms of an element are perfectly identical with one another. The size and shape of atoms are those of the ground state of atoms.

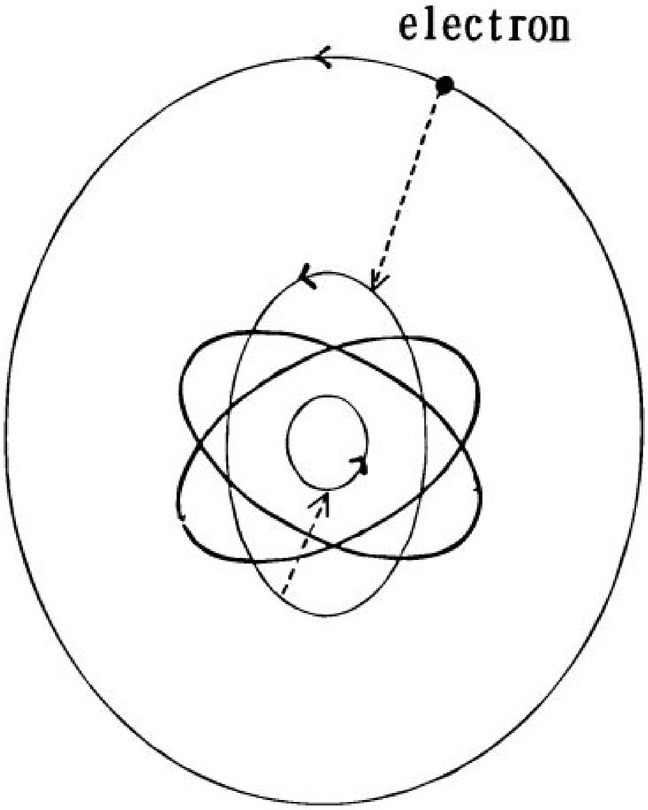

Figure 10. Emission of radiations from the excited states of a hydrogen atom

In general, any object of a finite size can be disintegrated into its constituents, and we can ask what is inside the object. This common sense based on our reductional thinking must have grown up through our daily experiences. The evolution of the atomic views in modern physics can be regarded as a splendid history, in which scientists repeatedly asked what is inside an object and successfully confirmed what is there.

Atoms, nuclei, and protons and neutrons are all of finite sizes. Sizes of atoms are $10^{-10} \sim 10^{-9}$ meter, sizes of nuclei are $10^{-15} \sim 10^{-14}$ meter, and sizes of the proton and neutron are about 10^{-15} meter. Thus they are all composite particles with their own internal structures. On the other hand, electrons are pointlike particles and only the upper limit of its size is known at present.

In breaking an object into its constituents, we usually strike an energetic particle against the object. In 1911, Rutherford found the existence of nuclei in atoms through experiments, in which he bombarded atoms with energetic alpha particles (helium nucleus) coming out from radioactive elements. Later experiments of similar types confirmed that every nucleus consists of protons and neutrons. Let us take an object which looks like a densely packed matter. There are two alternative possibilities for the constitution of the object. The object is filled more or less uniformly with its constituent matters, or the object is almost an empty space everywhere except those small spots where constituent matters are localized. In the former case the object is like a plain pudding and in the latter case the object is like a pudding with scattered grains of raisin in it.
When we bombard an energetic particle against the object, the particle will easily penetrate the object and it will be only a little deflected in the former case. When a particle hits a grain of raisin by chance, it will be deflected by a large angle in the latter case. Thus we can reveal the internal structure of an object through study of deflection patterns of energetic particles in their collisions with the object. In Fig.11 we illustrate typical features of the deflection of particles by the two types of objects.

In order to liberate the constituents of an object from it, we have to give enough energy to them to overcome the binding force between the constituents through collisions with incident particles. To unbind atomic bonds in a molecule and dissociate the molecule into atoms, energies liberated in exothermic chemical reactions or thermal energies available at high temperatures would be sufficient in most cases. To unbind electrons in atoms, a little more energy would be needed. To liberate protons or neutrons from nuclei, we need energies about 10^5 to 10^6 times as large as the energies to unbind electrons from atoms. Particles with high enough energy were not available until the end of the 19th century, and thus atoms were considered as the indivisible smallest units of matter. In the 20th century it became possible to use high-energy particles from radioactive elements and even to use artificially accelerated high-energy particles as the incident particles in collision, thus making it possible to endow enough high energies to a microscopic object under study and break it into its constituents.

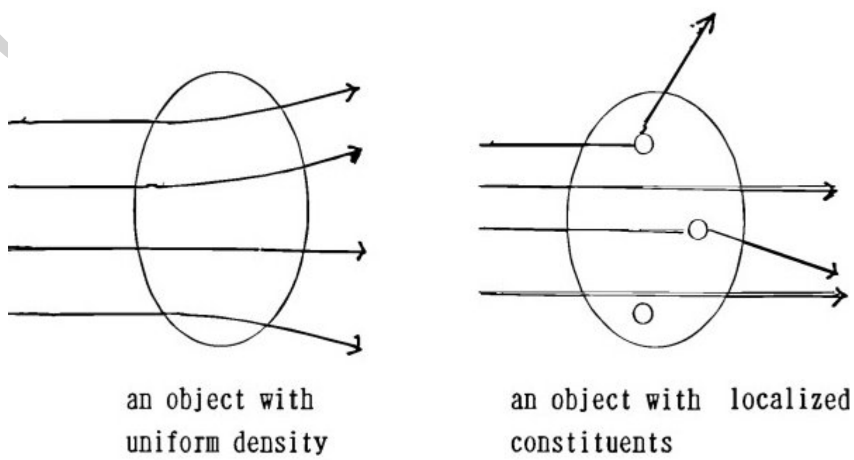

Figure 11. Deflection of particles by two kinds of objects

As a result, the internal structures of atoms, nuclei, and protons and neutrons were revealed. Atoms consist of electrons and a nucleus, nuclei consist of protons and neutrons, and protons and neutrons consist of quarks. Thus the most fundamental constituents of matter are not atoms any more, but instead quarks and electrons at the present time.

There are six kinds of quarks and six kinds of electron-like particles known to exist, the latter's are called leptons. These particles are listed in Table 1. Like protons, neutrons, and electrons, all the quarks and leptons have their own antiparticles.

Quarks			*Leptons*	
	Charge			*Charge*
u (*up quark*)	$(2/3)e$		ν_e (*electron neutrino*)	0
d (*down quark*)	$-(1/3)e$		e^- (*electron*)	$-e$
c (*charm quark*)	$(2/3)e$		ν_μ (*muon neutrino*)	0
s (*strange quark*)	$-(1/3)e$		μ^- (*muon*)	$-e$
t (*top quark*)	$(2/3)e$		ν_τ (*tau neutrino*)	0
b (*bottom quark*)	$-(1/3)e$		τ^- (*tau lepton*)	$-e$
Antiquarks			*Antileptons*	
$\overline{u}$	$-(2/3)e$		ν_e	0
$\overline{d}$	$(1/3)e$		e^+ (*positron*)	$+e$
$\overline{c}$	$-(2/3)e$		ν_μ	0
$\overline{s}$	$(1/3)e$		μ^+	$+e$
$\overline{t}$	$-(2/3)e$		ν_τ	0
$\overline{b}$	$(1/3)e$		τ^+	$+e$

Table 1. Quarks and leptons.

Quarks and leptons are the most fundamental particles in modern physics. As far as experiments told us, these particles are all pointlike and only the upper limits of their sizes are known at present. For example, the size of the electron is less than 10^{-4} times of the sizes of protons and neutrons and could be much less than the present upper limit. If these particles are really pointlike, they are worthy to be called atoms in modern days, and our search for the fundamental particles might have reached the extreme limit of the atomic view.

There are some peculiar properties about quarks which were revealed through experiments. First, quarks have fractional charges either $2e/3$ or $-e/3$, where e is the fundamental unit of charge found by Millikan or, equivalently, the charge of the proton. There is no principle to prevent a particle having a fractional charge, but no one has ever observed a particle with a fractional charge. This means that a single isolated quark is unlikely to exist and quarks are always found in composite systems which consist of several quarks and antiquarks.

For example, the proton and the neutron consist of three quarks, the antiproton and the antineutron consist of three antiquarks, and pions consist of a quark and an antiquark (see Development *of Fundamentals in Physics*). These particles called hadrons. All of them have charges which are integral multiples of the elementary charge *e*. The quarks always exist in a form of hadron and no single quark or antiquark seems to exist. This is called the quark confinement problem, which is now well understood based on the modern theory of quarks and their interactions. In a later chapter (see *Development of Fundamentals in Physics*) we shall discuss quarks and leptons in more detail.

Fields

So far we have described the atomic view that the matter consists of atoms, atoms consist of electrons and a nucleus, and then even nuclei consist of quarks. These constituents of matter are all discrete entities which are localized in space.

Faraday (1791-1867) was the first person who introduced the concept of field in modern physics. Two magnets attract each other through the static magnetic force. Likewise, two charged bodies exert each other the electrostatic Coulomb force. Both the electric and magnetic forces are action at a distance, which can act between two bodies distant apart. However, already at the time of Faraday, there existed a concept originated from Decultus, that an action at a distance should be mediated through some medium filling the space between the interacting two bodies.

If we sprinkle iron filings over a sheet of paper which is put on a bar magnet, the iron filings form a figure which consists of many curved lines connecting the two magnetic poles of the bar magnet as shown in Fig.12. Each iron particle behaves as a tiny compass needle and orients along the direction of the magnetic force of the bar magnet. Faraday named these lines the magnetic field lines.

He speculated that the magnetic field lines are physical realities and exist as real entities even when iron filings do not exist. A magnet sends out its field into space along field lines and any compass needle or magnet in space is acted by the field. Magnet-field-magnet was Faraday's answer to the magic of action at a distance (see *Quantum Systems*).

Magnetic fields can be plotted by means of tiny compass needles (called the test needles) such as filings. The direction in which the test needle points is taken to be the direction of the magnetic field. The magnetic field lines are drawn in such a way that a test needle placed on the line will align itself tangentially to the line. The strength of the magnetic field is defined in terms of the magnetic force on a test needle of unit strength.

In complete analogy to the magnetic field, Faraday introduced the electric field. If, at a certain point in space, a tiny positive charge (called the test charge) experiences an electric force, we say that an electric field exists at that point. The direction of the electric field is taken to be the direction of the electric force on the positive test charge. The strength of the electric field is defined in terms of the force on a positive test charge of unit strength. Electric field lines can be plotted in the same way with the magnetic field lines.

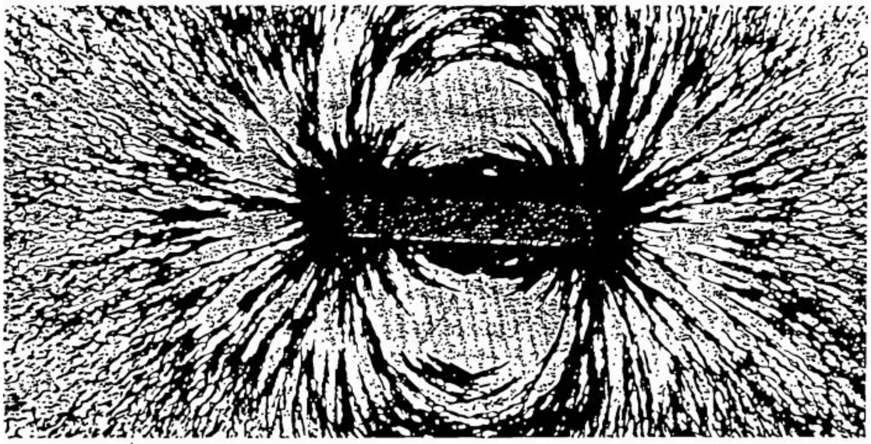

Figure 12. Iron filings lining up in the vicinity of a bar magnet

In Fig.13 we show electric field lines due to a pointlike positive or negative charge. The field lines run radially outward from the positive charge and inward into the negative charge.

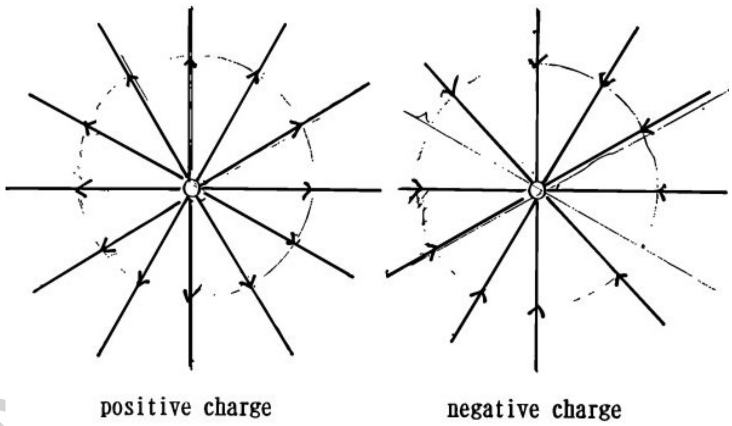

Figure 13. Electric field lines due to point chanrges

As another example, we show the electric field lines about two equal point charges. Fig.14 shows two possible cases, unlike charges and like charges. The electric field lines of Fig.14a is similar to the magnetic field lines of Fig.12, which is expected because a bar magnet has positive and negative poles of equal strength at its two ends.

The theory of the electromagnetic field was formulated by Maxwell as Maxwell's equations (see Development *of Fundamentals in Physics – Electricity and Magnetism*). As long as sources of fields, charges or magnets, are at rest and the lines of forces are time independent, the two conceptions of field and action at a distance are essentially equivalent. However, if the sources oscillate in time, disturbances of the field caused by the oscillation propagate through space as waves of the electromagnetic field and they exert electromagnetic forces on bodies at a distance when the waves arrive at the positions of the bodies.

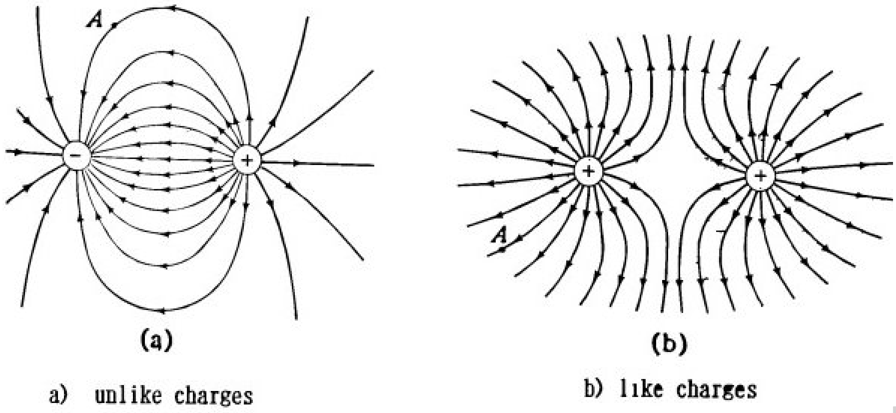

Figure 14. Electric field lines around pairs of equal point charges

Faraday was not very confident in the existence of the electromagnetic field as a real entity. But he expressed that, although he did not know how the magnetic force is mediated through matters or space, he was inclined to think that the force is mediated by some medium located outside the magnets, rather than the force acting directly on objects at a distance. He even considered the ether as a candidate of the medium.

In modern physics every force is associated with its field. Similar to the electromagnetic field, the gravitational force is associated with the gravitational field (see *Physical Systems and Laws Special and General Relativity*). These fields are produced by their sources. The electromagnetic field is produced by charges or magnets and the gravitational field is produced by massive bodies. When sources oscillate in time, they produce oscillating fields which can propagate in space as waves. It was first demonstrated by Hertz that an oscillating electric circuit produces an electromagnetic wave which propagates with light velocity to far distances and the wave was experimentally detected.

The nature of the force field has been extensively studied in the 20^{th} century. When a wave of any force field interacts with a microscopic object such as an atom or a fundamental particle, the wave behaves as if it were a localized object propagating through space. This corpuscular nature of waves was found for any wave of the force field. These particles are called quanta of the force fields (see *Quantum Systems*).

The quantum of the electromagnetic field is the photon and that of the gravitational field is the graviton. The strong force between quarks is mediated by the gluon field and its quantum is the gluon. All these quanta behave like particles and they all are massless particles. The so-called weak forces between quarks and leptons are mediated by the weak fields and their quanta are massive particles called weak bosons. All these fundamental force fields can be derived from the same gauge principle applied to interacting quarks and leptons, Therefore, the force field is called the gauge field and its associated quantum is called the gauge particle, Since quantum mechanics is an indispensable tool to understand the quantum nature of the force field and the gauge principle, we shall discuss the quantum nature of the field in more detail in a later chapter (see *Quantum systems*).

As we have implied, a force field has a dual nature of being a particle and a wave at the same time. In the same way, particles such atoms, nuclei, protons, neutrons, and quarks and leptons behave as waves under appropriate circumstances. For example, a beam of electrons can produce a diffraction pattern on a screen, which is a manifestication of the wave nature of the electron (see *Quantum Systems – Quantum Mechanical Laws*).

As exemplified by the wave nature of particles, any particle is associated with its corresponding field. According to quantum mechanics, the field of a particle is the wave function of the particle which gives the probability distribution of the position and momentum of the particle. The only reason why we do not usually notice the wave nature of a particle is due to the fact that the wavelength is too short to be detected under ordinary circumstances and the wave is quite well localized in space.

We have seen that the matter consists of six kinds of quarks and leptons. Also we have seen that the fundamental forces between the quarks and leptons are mediated by quanta of the force fields, which behave as particles. Therefore, our universe consists of quarks and leptons together with gauge particles (photons, gluons, weak bosons and gravitons).

Although almost all the phenomena in atomic scales have been well understood based on the modern theory of elementary particles incorporating quarks, leptons, and gauge particles in it, many physicists speculate that there might be some additional fundamental particles present in nature. These particles have been and still are being extensively searched for.

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Biographical Sketch

Gyo Takeda, Professor Emeritus of Tokyo University and Tohoku University, was born in Tokyo l924. His speciality is the theory of Particle physics and nuclear physics and he also carries out research into neuroscience. He is known as one of the collaborators of Prof. S. Tomonaga's works on the relativistic renormalized theory of quantum electrodynamics. After graduating from Physics Department, University of Tokyo, he has served as an Associate professor, Kobe University, Professor and Director, Institute for Nuclear Studies, University of Tokyo, Professor of Physics and Dean of Faculty of Science, Tohoku University, and a Professor, General Education, Tohoku Gakuin University. Also he served as a research associate of University of Wisconsin and Brookhaven National Laboratory, USA, during the period of 1952-l955 and as a visiting professor of University of Wisconsin and University of California, Berkley, during the period of l96l-l963. He was a member of High Energy Physics Committee of IUPAP(International Union of Pure and Applied Physics) during the period of l973-l978 and served as the Chairman of the Organizing Committee of the l7th International High Energy Physics Conference held in Tokyo, l978. He has published many textbooks on general physics, quantum field theory, particle physics, and neuroscience all in Japanese.