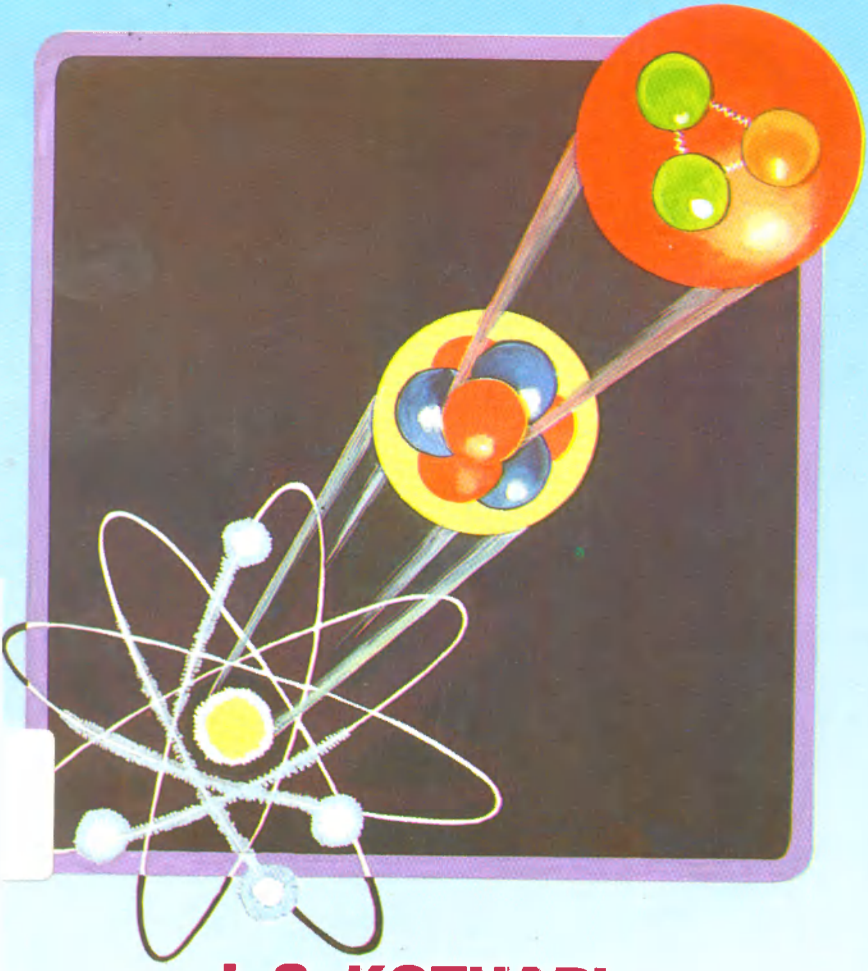
CSIR GOLDEN JUBILEE SERIES

INSIDE ATOMS



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Foreword

The Council of Scientific & Industrial Research (CSIR), established in 1942, is committed to the advancement of scientific knowledge, and economic and industrial development of the country. Over the years CSIR has created a base for scientific capability and excellence spanning a wide spectrum of areas enabling it to carry out research and development as well as provide national standards, testing and certification facilities. It has also been training researchers, popularizing science and helping in the inculcation of scientific temper in the country.

The CSIR today is a well knit and action oriented network of 41 laboratories spread throughout the country with activities ranging from molecular biology to mining, medicinal plants to mechanical engineering, mathematical modelling to metrology, chemicals to coal and so on.

While discharging its mandate, CSIR has not lost sight of the necessity to remain at the cutting edge of science in order to be in a position to acquire and generate expertise in frontier areas of technology. CSIR's contributions to high-tech and emerging areas of science and technology are recognised among others for precocious flowering of tissue cultured bamboo, DNA finger-printing, development of non-noble metal zeolite catalysts, mining of polymetallic nodules from the Indian Ocean bed, building an all-composite light research aircraft, high temperature superconductivity, to mention only a few.

Being acutely aware that the pace of scientific and technological development cannot be maintained without a steady influx of bright young scientists, CSIR has undertaken a vigorous programme of human resource development which includes, inter alia, collaborative efforts with the University Grants Commission aimed at nurturing the budding careers of fresh science and technology graduates.

However, all these would not yield the desired results in the absence of an atmosphere appreciative of advances in science and technology. If the people at large remain in awe of science and consider it as something which is far removed from their realms, scientific culture cannot take root.

CSIR has been alive to this problem and has been active in taking science to the people, particularly through the print medium. It has an active programme aimed at popularization of science, its concepts, achievements and utility, by bringing it to the doorsteps of the masses through both print and electronic media. This is expected to serve a dual purpose. First, it would create awareness and interest among the intelligent layman and, secondly, it would help youngsters at the point of choosing an academic career in getting a broad-based knowledge about science in general and its frontier areas in particular. Such familiarity would not only kindle in them deep and abiding interest in matters scientific but would also be instrumental in helping them to choose the scientific or technological education that is best suited to them according to their own interests and aptitudes. There would be no groping in the dark for them. However, this is one field where enough is never enough.

This was the driving consideration when it was decided to bring out in this 50th anniversary year of CSIR a series of profusely illustrated and specially written popular monographs on a judicious mix of scientific and technological subjects varying from the outer space to the inner space. Some of the important subjects covered are astronomy, meteorology, oceanography, new materials, immunology and biotechnology.

It is hoped that this series of monographs would be able to whet the varied appetites of a wide cross-section of the target readership and spur them on to gathering further knowledge on the subjects of their choice and liking. An exciting sojourn through the wonderland of science, we hope, awaits the reader. We can only wish him Bon voyage and say, happy hunting.

Preface

Ever since man (homo-sapiens) developed the faculty of thinking, many apparent features of nature attracted his attention. Sky with its twinkling stars, constellations, sun, moon and the milky way have always charmed him. Man's curiosity to know them has led to the development of his knowledge about the cosmos. Another enigma that centered around later, was ATOMS. The methods of scientific experimentation and not merely philosophical speculations (though these have proved to be extremely important at times), have been largely responsible for the present knowledge about them. Only those conjectures which stood the caustic experimental verifications survived. This also gave rise to many extremely useful applications of atoms. Though our knowledge of atoms is fairly advanced from what it was a few centuries ago, it is by no means complete. However, its story has many interesting developments and we thought that it would be worth narrating. *Inside Atoms* thus traces the various thought processes that led to our present understanding about them.

Acknowledgements

This book has been written at the inspiration and suggestion of the Late Prof. D.S. Kothari who guided our efforts as long as he was alive. We express our gratefulness to Dr. Krishan Lal of the National Physical Laboratory, New Delhi, for many useful discussion from time to time. The contacts with Dr. B. Subbarayappa (Bangalore) and Prof. V. Upadhyaya of Delhi University (Sanskrit Department) have benefited us a lot in writing about the ancient Indian view of atoms. Their help in this regard is thankfully acknowledged. Prof. Laurie M. Brown of Northwestern University, Chicago, USA, during his brief visit to Delhi University, was kind enough to glance through the manuscript and provided some valuable comments, for which we are very thankful to him. We are grateful to Dr. A. R. Verma for critically going through the manuscript.

We would like to thank Dr. G.P. Phondke, Director, P.I.D., for taking interest in this book. It has been ably edited by Mr. Biman Basu and Mr. N.C. Mondal and we are thankful to them for all the hard work put in it. We are also thankful to Dr. Sukanya Datta for her help and particularly to Mr. Pradip Banerjee and his team for beautiful art work.

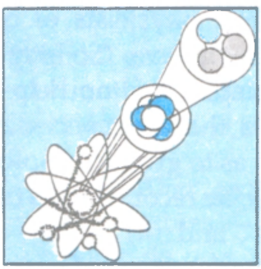
Dedicated

to

The Late Prof. D.S. Kothari

Contents

Early Concepts



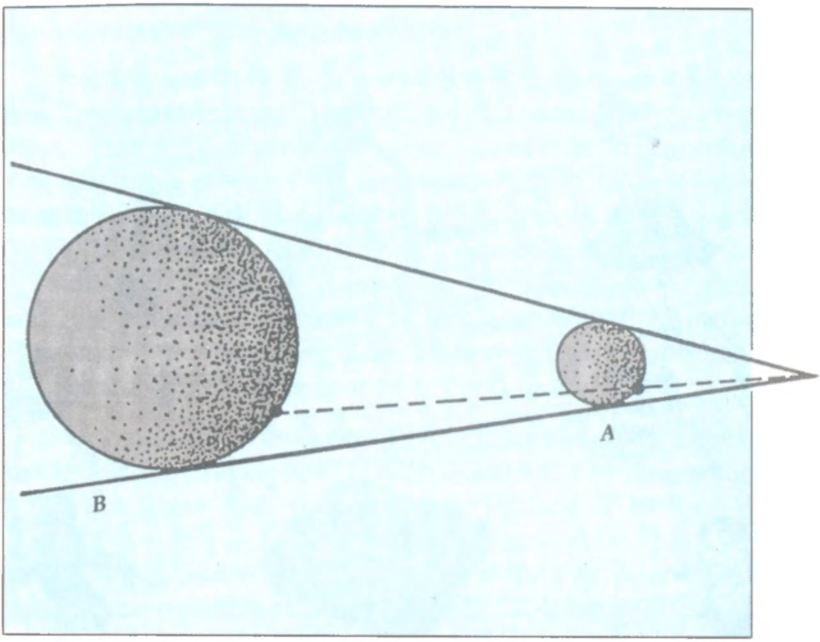
Man's greatest and probably the most revolutionary discovery in the physical sciences is that 'matter consists of atoms'. We now know enough about atoms to realise that we still do not fully understand what they are. The story of the development of ideas about atoms is very exciting.

When we try to understand something, we usually do that in terms of its parts; we try to understand the big in terms of the small. However, big and small are relative terms and this is nicely brought out in a story of Akbar and Birbal.

Akbar once drew a line on a sheet of paper and asked the members of his court as to whether it was long or short. The question puzzled the courtiers, but Birbal replied that the line was both long and short. When asked to explain his statement, Birbal drew two lines — one shorter and the other longer than the one drawn by Akbar. Birbal said that the line drawn by Akbar was longer than the shorter line, but shorter than the longer one.

Thus, if we want to study matter, it is no good trying to explain it in terms of its parts, because then the parts will have to be ex-

plained in terms of even smaller parts, and this process can never end. Then how can one understand matter? Paul A.M. DIRAC (1902-1984), one of the greatest physicists of our times, has something else to say on this. He says, "So long as *big* and *small* are merely relative concepts, it is no help to explain the big in terms of the small. It is, therefore, necessary to modify classical ideas in such a way as to give an absolute meaning to *size*". To understand matter, he recommends two things: (i) to give up 'classical ideas', and (ii) to give an absolute meaning to *size*. In science, by 'classical ideas' we mean all physics up to the end of the nineteenth century. Hence, what Dirac says is that science of the nineteenth century could not adequately explain matter, though it was greatly successful in many other ways. The idea of giving an absolute meaning to *size* first became possible only in this



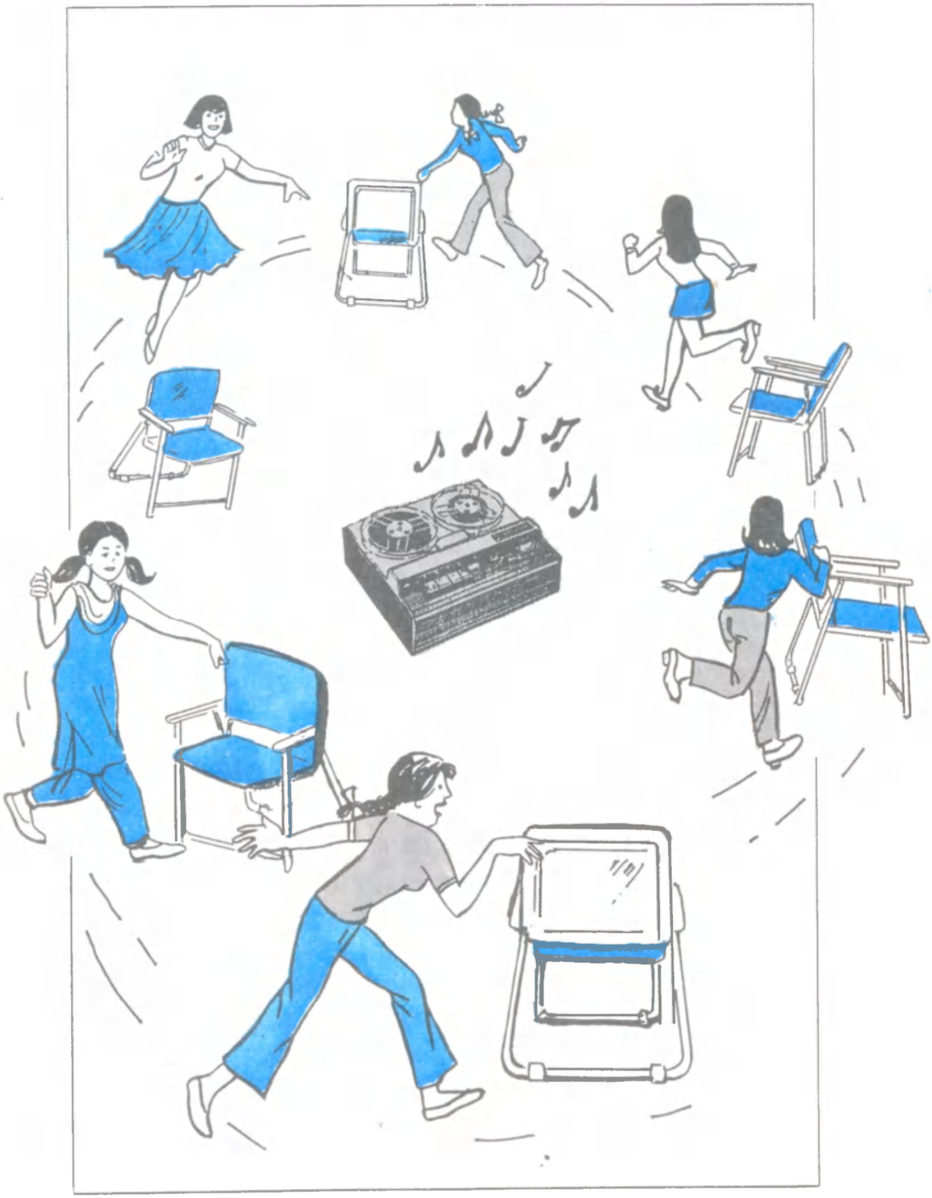
Comparing the number of points of two spheres A and B
(a three dimensional case)

century with the introduction of the concept of **Quanta (Photons)** of energy radiation.

Without giving absolute meaning to *size*, different properties of matter cannot be understood and the difficulty involved was realised by the early Greeks and Indians.

One peculiar geometrical observation was that, if we consider two lines — one short and the other long, then for every point on one, there is a corresponding point on the other. That is, the number of points on these two lines will have to be the same. The result will hold good in two and three dimensions as well.

For example, in a room with a set of chairs nicely arranged and a group of people, the number of persons is equal to the



One-to-one correspondence

number of chairs only if there is a one-to-one correspondence between the persons and the chairs.

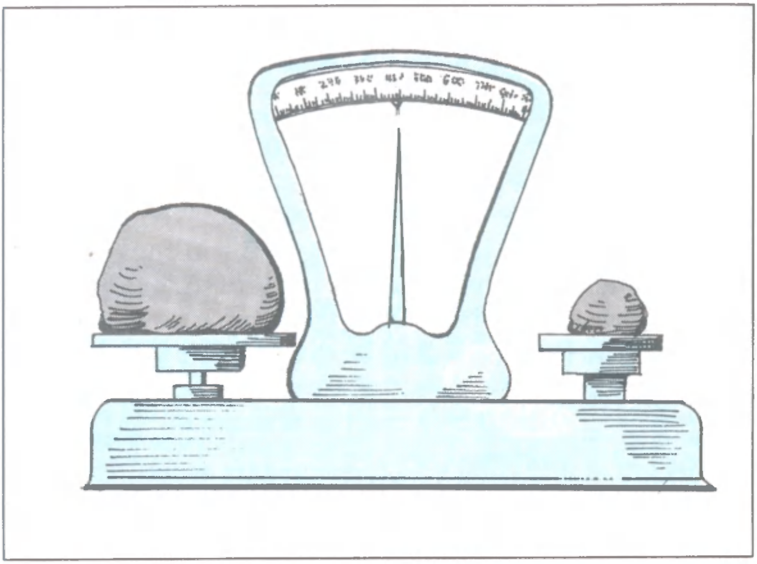
If matter was truly continuous as space, then according to this 'continuum model' it would exhibit some strange properties. Take a small piece of matter, say of iron, and another, a much larger piece, of the same material. According to the 'continuum model', the number of points in the two pieces would be the same. If with every point of iron we associate the same **mass**, then the mass of the two pieces — one small and the other large — would be the same since the number of points in the two is the same. However, this is not what is observed. Hence matter cannot be continuous.

This grave difficulty was overcome by the early Greeks, particularly, by DEMOCRITUS (460-380 B.C.) by assigning a small but finite size to the smallest particle of matter. He called it the *atom* — Greek word for unbreakable. This was a practical way out of a philosophical difficulty. Why should these atoms be unbreakable? As late as 1704, Isaac NEWTON (1642-1727) in his book *Optik*, wrote, "All those things being considered, it seems probable to me, God in the beginning formed matter in solid, massy, hard, impenetrable, movable particle..., so very hard as never to wear or break into pieces; no ordinary power being able to divide what God himself made one in the first creation..." This implies that for thousands of years the only reason for indestructible nature of atoms was a **theological** one.

Indian thinkers of antiquity, being highly logical in their approach, rejected the idea of finite size of atoms. They could not see any reason as to why nature should select one size and not some other, bigger or smaller.

Indian View

One can study and analyse any object in two ways: (i) by considering the object as a whole and examining its various functions or properties, and (ii) by taking the object apart into



Big and small weigh the same, a strange property of continuum model

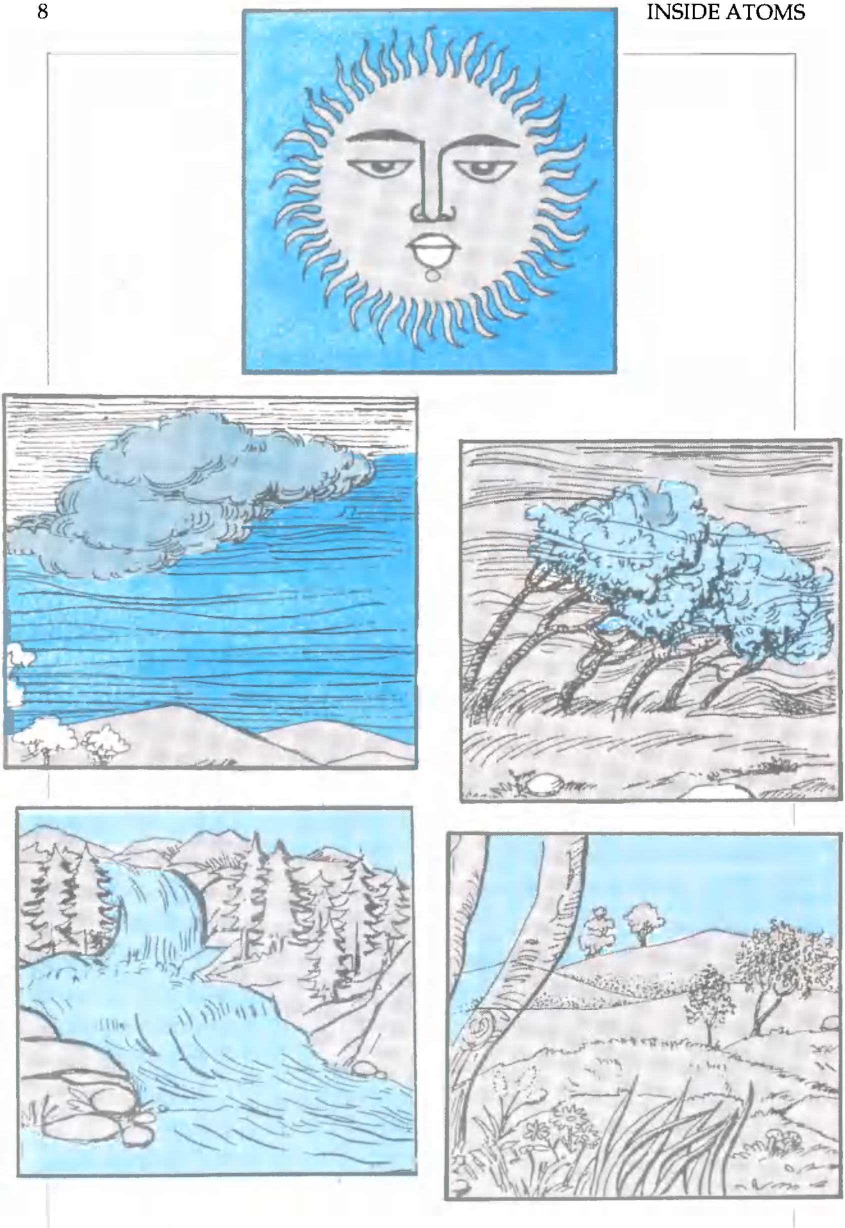
"So very hard as never to break"

its components and studying the different parts. Modern science follows the second approach, but it is now realised that, "the whole is not just a sum of its parts", and to this extent, the scientific method fails when we try to really understand a living system. The ancients preferred to follow the first approach, and analysed all objects in terms of the way they influenced the human senses associated with *gandha* (smell), *rasa* (taste), *roopa* (beauty), *sparsh* (touch) and *shabda* (sound).

Early Indians as well as early Greeks sought to find an 'essence', or a 'substance', or an 'element' out of which all things were made. The earliest records (2000-1500 B.C.; both Indian and Greek) consider water as this substance, since it is colourless, can flow easily and can take any shape. However, this concept was later modified greatly and advanced. There emerged the doctrine of five elements: *prithvi* (earth); *ap* (water); *tejas* (fire); *vayu* (air) and *akasa* (an ubiquitous entity). Among them the following four, namely, earth, water, fire and air were considered to be atomic, indestructible, indivisible and without any dimension. All atoms were regarded as spherical. These four different kinds of atoms possessed four different specific properties: atoms of earth had smell; atoms of air had touch; atoms of water had taste; and atoms of fire had colour. Atoms produce matter of visible form since they were in eternal motion and because of this, two or more atoms could combine. These ideas were developed over centuries by a number of sages.

However, the philosophical argument concerning the atoms was strongly criticised, specially by the great SANKARACHARYA (800 A.D.). To quote from the *Brahmasutra Bhasya* of Sri Sankaracharya, - "for, if one can resort to imagining the existence of things that do not exist, then anything can be proved to exist". He further says, "there is the additional argument. As the ultimate atoms are limited in size, they must have as many surfaces (or parts) as there are directions, be they six, eight, or ten, and having parts they will be impermanent. Thus the view that they are permanent and partless will be nullified."

Even so, atomism found a number of very able supporters in India till the 14th-15th centuries, when Greek atomism was lying dormant in the west. The earliest exponent of atomic theory in India was the sage KANADA (c.6th century B.C.). His teaching was modified by others around 10th century



Doctrinal five elements

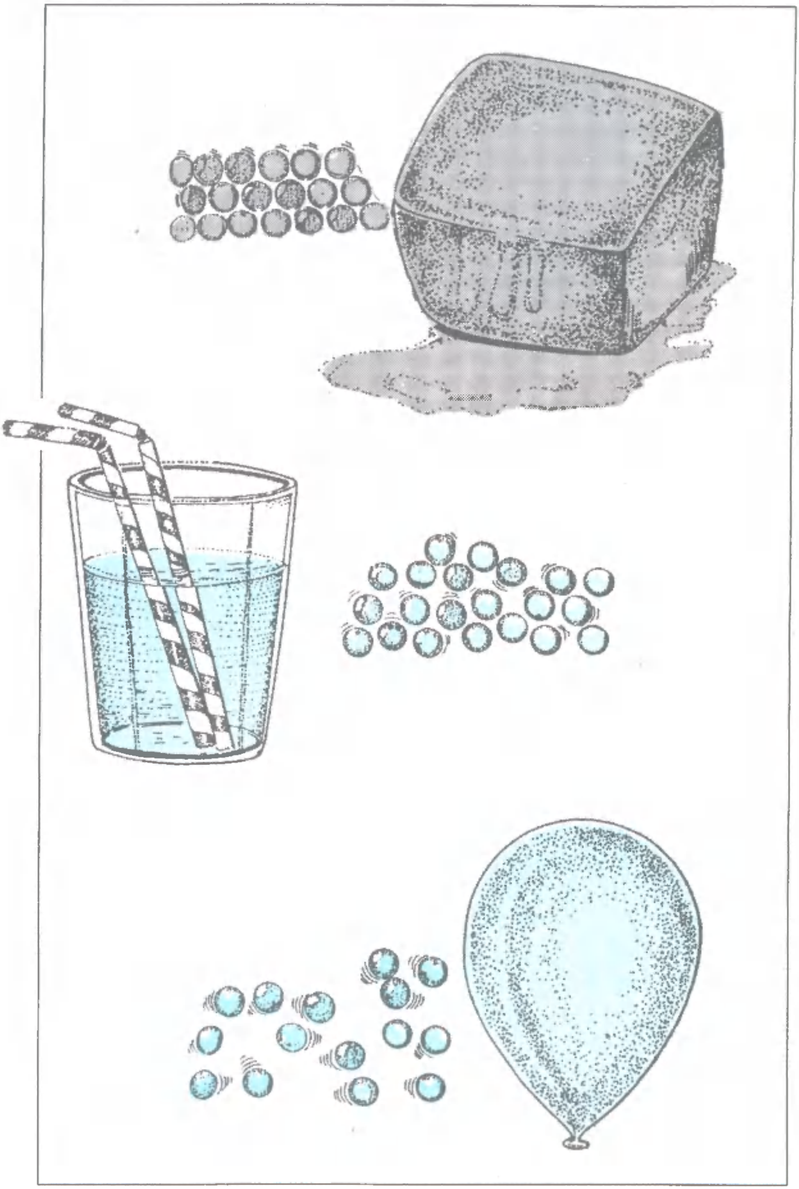
A.D. and came to be known as *Nyaya-Vaisesika* school of thought.

Greek View

LEUCIPPUS (around 450 B.C.) is referred to as the inventor of atomism. In order to remove the difficulties experienced in the continuum model of matter he suggested that matter consists of indivisible atoms of finite size. He is also credited with the law of causality in science. He stated, "nothing happens without reason, everything has a cause and is the result of a necessity". His work was carried forward and elaborated by his famous pupil, Democritus. According to Democritus, matter was made up of two things: atoms and empty space or void. Atoms were eternal, unchangeable and indestructible. They had different shapes which allowed them to join with one another and form different substances. He also postulated that human soul was atomic in nature.

The indestructible nature of atoms, or their stability, followed from the observation that all matter, left to itself, did not change its properties. Further, to explain the transformation of matter from one state to another, for example, ice to water to vapour, Democritus had to assume the reality of empty space. In such changes the relative separation between the atoms increased. Democritus suggested that properties of matter in a given state were determined by the properties of the atoms and their relative separation. Thus, in explaining the properties of matter the concept of void was as important as that of atoms.

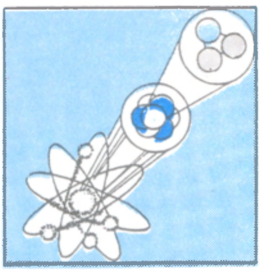
For the Greeks, all earthly matter could be thought of as being composed of four principles or substances, namely, earth, water, air and fire. Heavenly bodies needed one more substance called quintessence (fifth substance). These existed in various combinations with qualities of (i) hot and cold, and (ii) wet and dry.



Relative separation of atom increases from solid to liquid to gas

Thus we see that although the concept of atomic structure of matter was philosophically not acceptable, it was necessary to introduce this to be able to understand some basic properties of matter. The concept of **elements** as we know it to-day, began to develop only, three centuries ago.

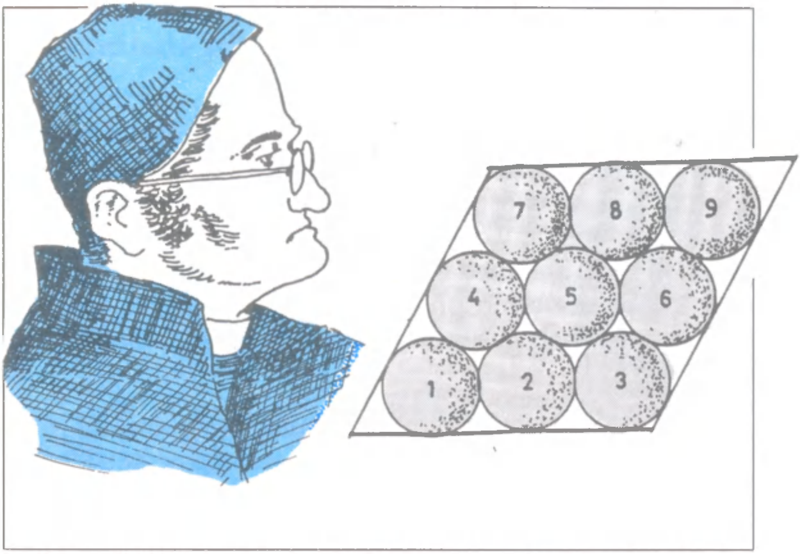
Towards Modernity



The Greek concept of atoms and of the four elements held sway till almost the middle of the seventeenth century, when Robert BOYLE (1627-1691), an English chemist, carried out extensive experiments on properties of gases and developed the modern concept of an element. According to him, an element was a material which could be identified by scientific experiment and could not be broken down into simpler substances.

Another great scientist who contributed greatly to our understanding of the true nature of elements was Antoine LAVOISIER (1743-1794), a French chemist. He provided the names for the two elements, oxygen and hydrogen, and showed that diamond was a form of carbon. He is also responsible for the present symbolic representation of chemical elements. He established the law of conservation of mass in chemical reactions.

However, it was John DALTON (1766-1844), a British scientist, who placed the atomic theory on a firm scientific foundation and is referred to as the Father of modern atomic theory. All his conclusions were based on experimental observations rather



John Dalton and his concept of atoms resembling numbered billiard balls

than on philosophical arguments. According to him, different atoms of an element were identical and the difference between elements arose from differences in the properties of atoms (including their masses), constituting the elements. Thus, an atom of hydrogen was considered lighter than an atom of copper. Atoms of the same or different elements could combine to form a group, called a molecule. The ratio of the atoms in a molecule (constituted by different atoms) was always the ratio of natural numbers.

In the development of the concept of the atom, the contributions of the Italian scientist Amedeo AVOGADRO (1776-1856) are also highly significant. He showed that all gases under the same conditions of temperature, pressure and volume contain the same number of molecules. For exmaple, 22.4 litres of hydrogen gas at **standard temperature** and **pressure** (S.T.P) contain 6×10^{23} molecules of hydrogen (mass of 22.4 litres of hydrogen gas will be 2 grams).

The magnitude of this number is best appreciated when we realise that we still inhale part of Buddha's last breath.

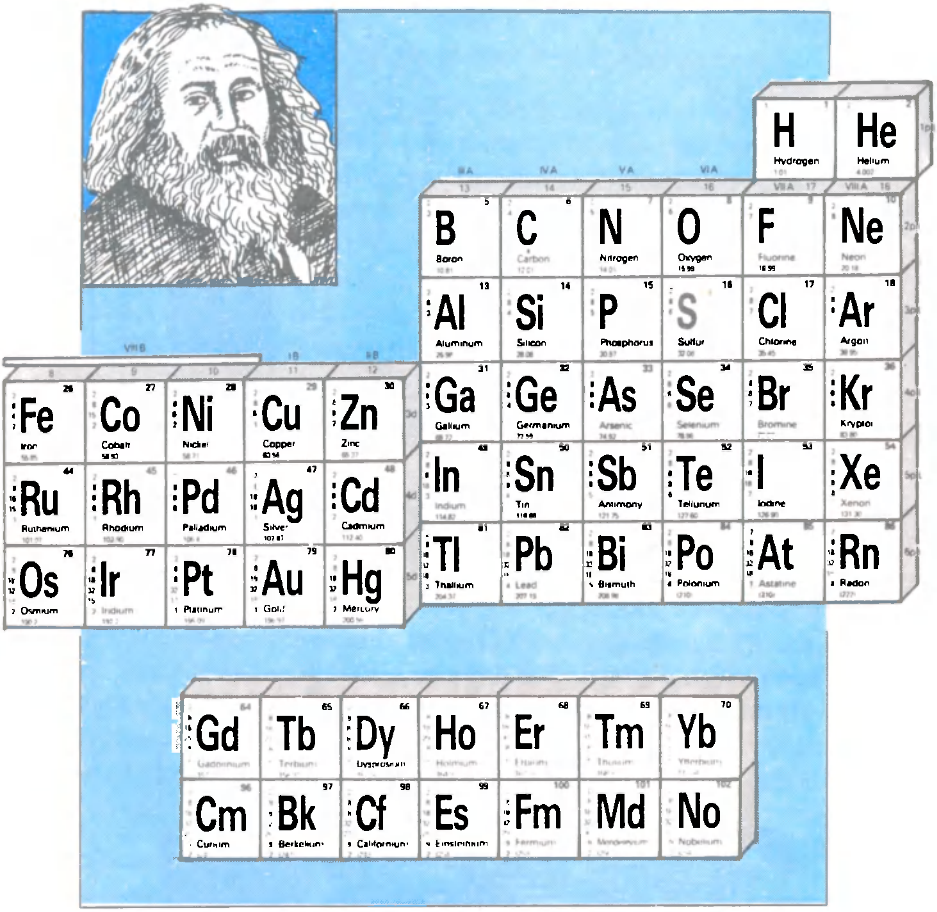
Think of the last 100 breaths of the Buddha, and the atoms of argon in it. Each one of us, in every 10 minutes, breathes in at least one atom of argon from those 100 breaths of the Buddha. We have chosen argon because it is an inert gas and does not undergo any chemical reactions under normal conditions. What is breathed in, is breathed out. Further, it forms about 1% of the atmosphere (0.93% to be more precise), whereas other inert gases like neon or helium constitute less than 0.002%.

Take the volume of air in each breath as 300 millilitres. Then the number of argon atoms in this volume at STP will be 8×10^{19}. The mass of the total atmosphere is nearly 5.27×10^{18} kilograms. It is estimated that in about 10 years time the total air in the atmosphere is completely mixed. Thus, by now the argon atoms from those last 100 breaths of the Buddha would have got thoroughly mixed in the atmosphere. Hence, each gram of air will contain nearly 0.015 argon atom. In other words, nearly 70 grams of air contain 1 argon atom from the last breath of the Buddha. We breathe in this much of air in about 10 minutes. That means we breathe in at least 1 argon atom during this time.

As another example, take an electric bulb and imagine that it has been totally evacuated. Suppose it develops a tiny leak through which a million molecules of air rush in every second. If the volume of the bulb is 150 millilitres, what do you think will be the time required for the pressure inside the bulb to become equal to the air pressure outside? One can calculate that this time would be roughly 125 million years, — quite strange to imagine.

By the middle of the nineteenth century, about 60 elements had been discovered. The properties of different elements differed greatly from one another and no obvious correlation in their properties could be observed. Some were gases like

Last breaths of the Buddha



Mendeleev and the Periodic Table

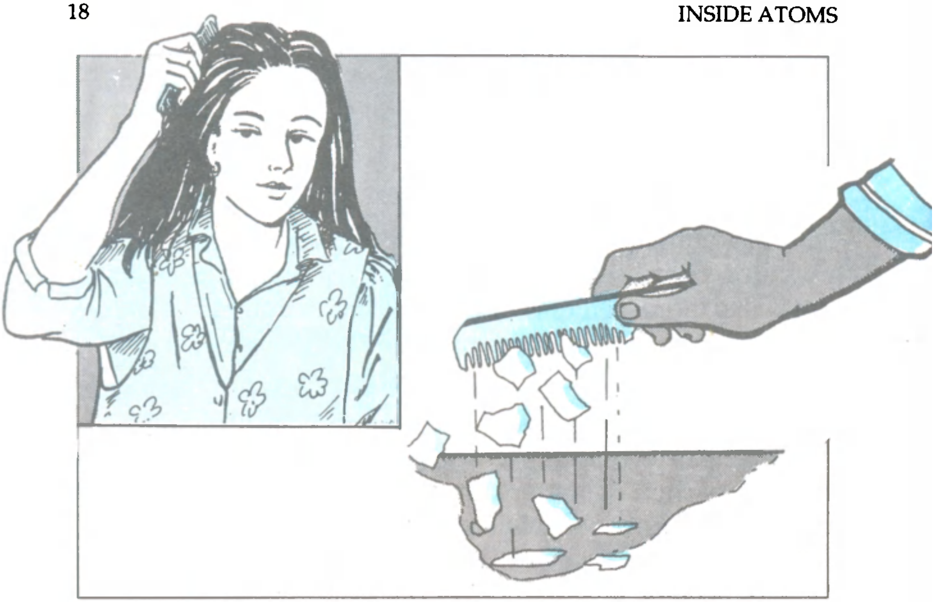
hydrogen, oxygen and nitrogen; some solids like sodium and potassium reacted with oxygen, whereas some like silver, gold and platinum were termed noble metals. The discovery of any new element came as a total surprise and its properties had to be studied in detail. However, in 1869, the great Russian scientist D.I. MENDELEEV (1834-1907) was able to arrange the then known 63 elements in a tabular form which led to the discovery of the Periodic Table. Some cells in his

Periodic Table remained empty and Mendeleev could predict the existence of these missing elements along with their properties. In 1875, the French chemist Lecoq de BOIS-BAUDRAN (1838-1912) discovered a new element with **atomic number** 31, similar in properties to aluminium and having a **density** of nearly 6×10^3 kilograms per cubic metre, exactly as predicted by Mendeleev. Within the next seven years two more elements, namely, scandium and germanium were discovered. Subsequently another 30 elements were discovered.

This important discovery of the periodic recurrence in the properties of elements led Mendeleev to surmise that the smallest particle of matter known at that time, the atom, must itself be composed of yet smaller units. To quote him, "although it cannot be proved as yet, it is easy to assume that the atoms of elementary bodies are complicated species consisting of even smaller particles... My periodic relationship between the properties and the **atomic weight** seems to confirm this expectation." One had to wait almost another 25 years before any concrete experimental evidence could be discovered for confirming his conjecture.

You must have noticed that a plastic comb when used on dry unoiled hair gets charged and can attract tiny pieces of paper. Much before plastics were discovered, glass rods rubbed with silk and ebonite rods rubbed with wool were used to demonstrate this phenomenon. This was known even to ancient Greeks and the word electricity originates from the Greek word for amber (a yellow transparent resin). The connection between **static electricity** and structure of matter was not clear till almost the end of the last century.

Benjamin FRANKLIN (1706-1790), a great American scientist and statesman, performed a number of experiments to obtain a better understanding of electricity. In his famous experiment of flying a kite during a thunder storm he demonstrated the electrical nature of lightning. Franklin reasoned that electricity was a kind of fluid, and an object with an



A charged comb attracts paper pieces

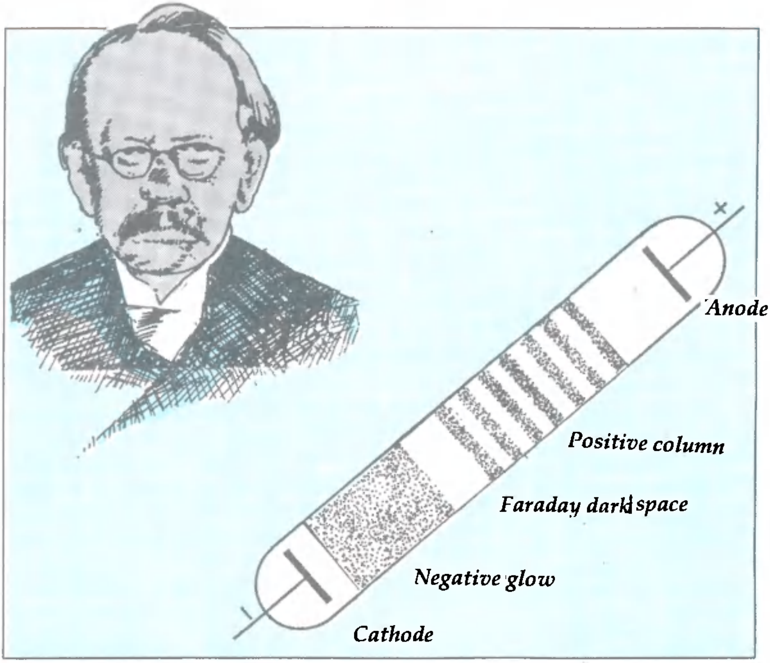
excess of electricity attracted an object that was deficient in this fluid and called them positive and negative electrical states, respectively.

However, concrete evidence about the nature of electricity was first provided by the classic experiments of the great British physicist, Sir J.J. THOMSON (1856-1940) on the discharge of electricity through gases. Thomson observed that irrespective of the nature of the gas in the discharge tube, particles passing through the perforations in the positive electrode, called the anode, had identical properties. All these particles had the same charge and the same mass. This was demonstrated by Thomson by measuring the ratio of their charge to mass. Since these particles were observed to come out from behind the anode, they must carry a negative charge. These particles were named electrons. It is only a matter of convention that we call the charge on an electron negative. They were extremely small in dimensions.

Benjamin Franklin and his kite flying

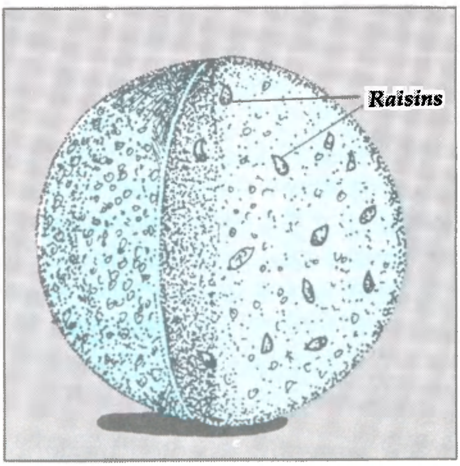
Thomson rightly concluded that electrons must be one of the constituents of the gases in the discharge tube and hence of all matter. Since matter is known to be electrically neutral, there must also exist positive charges in matter. Thomson proposed a model for an atom. It was something similar to a *laddoo* with raisins interspersed. The raisins represent electrons dispersed in a uniform positive charge, the total positive charge being equal to the total negative charge.

The presently accepted model of the atom is, however, quite different from this and was established by a series of experiments in an entirely different area of physics.

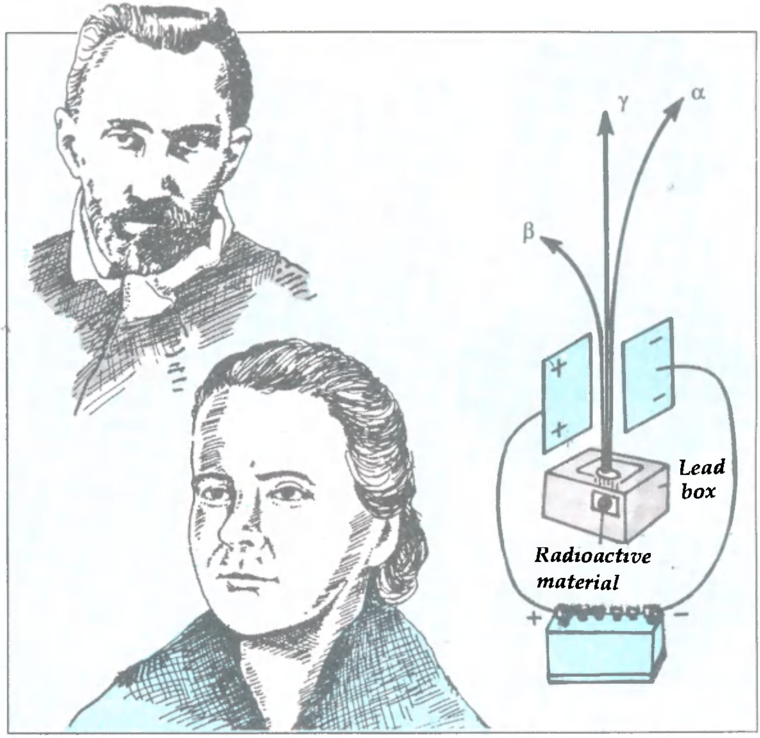


J.J. Thomson and discharge of electricity through gases

The French physicist Henry BECQUEREL (1852-1908), while studying the phenomenon of **fluorescence**, observed that when salts of uranium wrapped in black paper were left on a photographic plate, then on developing, the plate became fogged. This led to the discovery of the phenomenon of **radioactivity**. It was

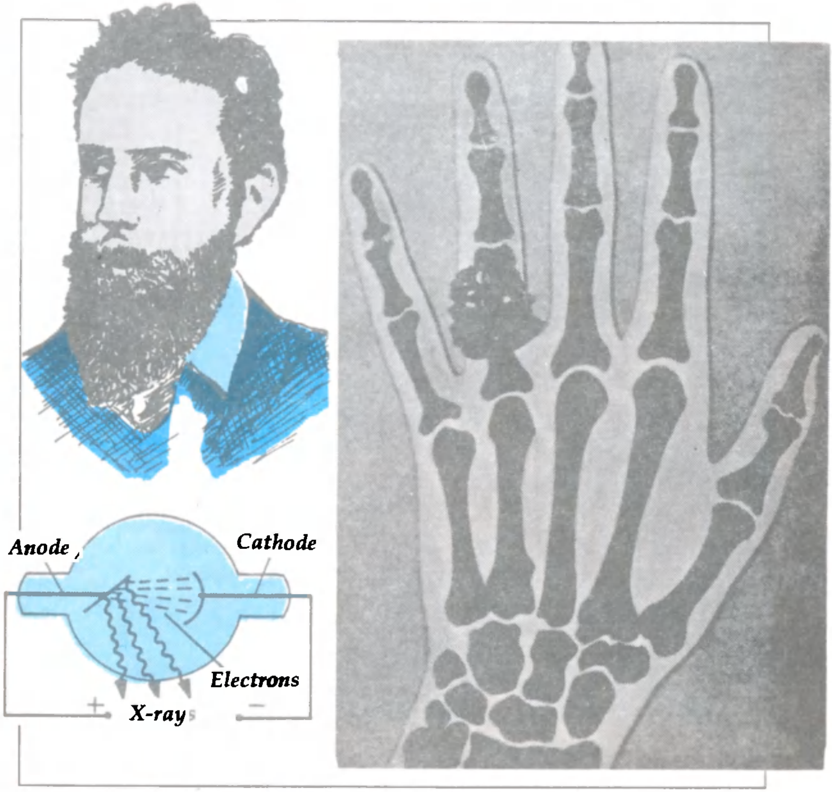


Laddoo with raisins interspersed



Pierre Curie, Marie Curie and the
alpha (α), *beta* (β)and *gamma* (γ) radiation s

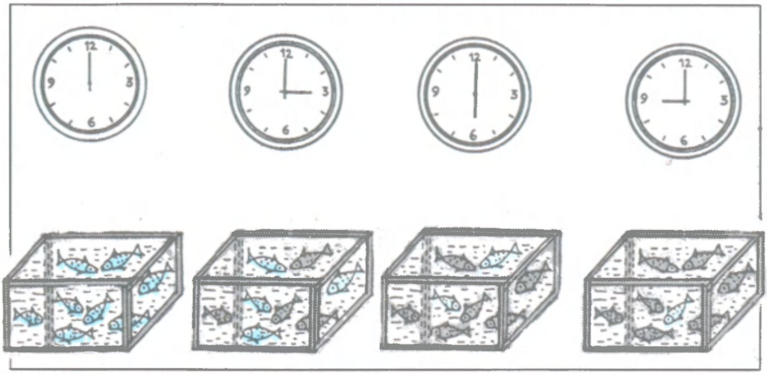
studied in much greater detail by Pierre CURIE (1859-1906) and Marie CURIE (1867-1934) who discovered other radioactive elements — polonium and radium. They also discovered that radioactive substances emit three types of radiation, which were named as *alpha* (α), *beta* (β) and *gamma* (γ) radiations. The *alpha* radiations are massive positively charged particles, while *beta* radiations are negatively charged light particles and *gamma* radiations are electrically neutral. The *alpha* particles are identified as helium nuclei, the *beta* radiations are identified with electrons and *gamma* radiations with very short wavelength **electromagnetic radiations**. We know that X-rays were also discovered towards the end of the last



Roentgen, his historical X-ray photograph of his wife's hand showing the wedding ring and the early X-ray tube

century by Wilhelm Konrad ROENTGEN (1845-1923), the great German physicist.

In the study of the properties of the three radiations, a major role was played by the English physicist, Lord Ernest RUTHERFORD (1871-1937). Born in New Zealand, a British colony, he moved to Cambridge on a fellowship for research. At the age of twenty seven, in 1898, he was appointed as a Professor at the Mac Donold Institute in Montreal, Canada. He moved to Manchester University, U.K, in 1907 and then to Cambridge University in 1919, where he succeeded Thomson.

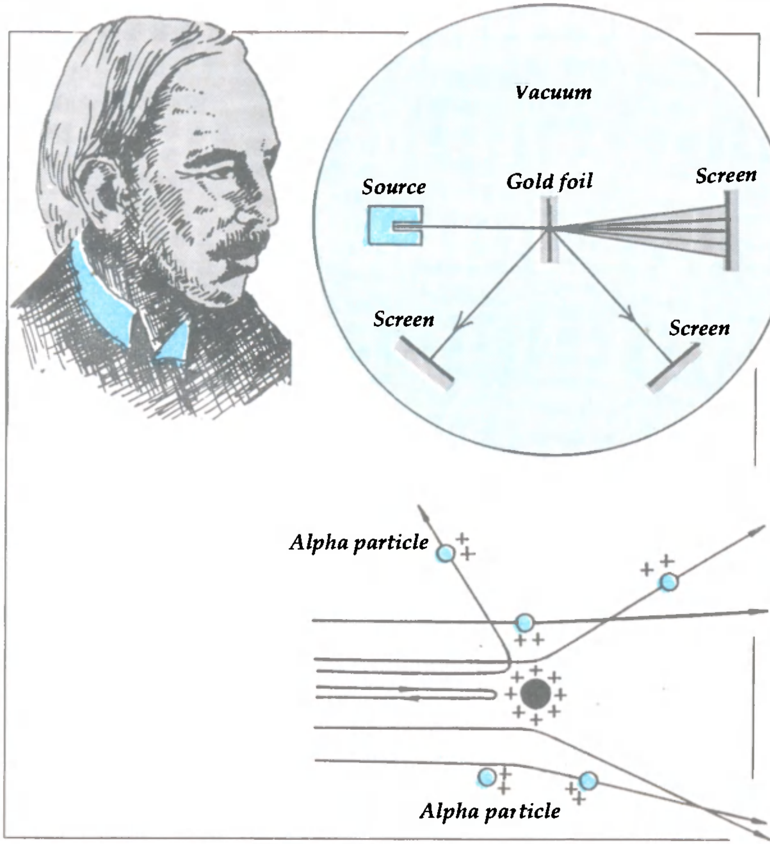


Every three hours, half of the blue fish turning into grey — a concept of half-life of 3-hours

While studying the phenomenon of radioactivity, it was soon discovered that when a particular atom of an element emits an *alpha* particle or a *beta* particle, it is transformed into a **nucleus** of some other element. Thus the number of original radioactive atoms decreases with time. It was observed that the number of radioactive atoms decaying in a given small interval of time is directly proportional to the number of such atoms present at that time.

The time in which the number of radioactive atoms is reduced to half the original number is called the 'half-life' of the radioactive element. The half-life is independent of the amount of radioactive atoms we start with and is also a characteristic of the material.

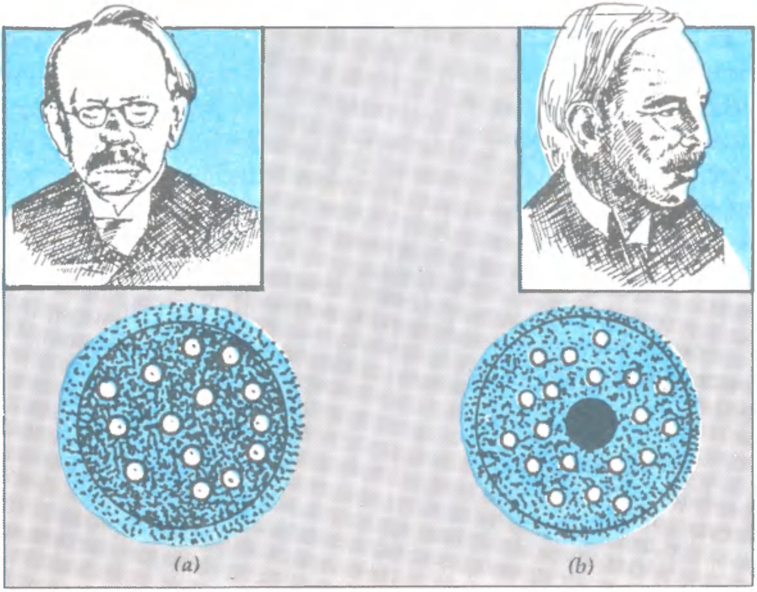
Rutherford's experiments were simple and precise. An experiment which was carried out with one of his research students E.MARSDEN (1889-) and assistant Hans GEIGER (1882-1945), completely changed the model of the atom as it existed at that time. This experiment was to study the **scattering** of *alpha* particles (emitted from radioactive atoms) from thin metallic foils. To the surprise of the experimenters they observed that a few of the *alpha* particles, on hitting the metal foil, turned back by almost 180 degrees. This was like



Rutherford and scattering of *alpha* particles by thin gold foil (top); Possible trajectories (indicated by arrows) of *alpha* particles incident on an atom (bottom)

a bullet being reflected back when fired into a haystack. Such large angle scattering could not be explained on the basis of the atomic model proposed earlier by Thomson.

To explain this large angle *alpha* particle scattering, Rutherford proposed that the positive charge of the atom should be concentrated in a very small region of space and this should also carry almost the entire mass of the atom. This model is now referred to as the Rutherford model or the nuclear model of the atom.



Thomson model (a) and Rutherford model (b)

According to this model the positive charge and almost the entire mass is concentrated in a small central region of the atom, called the nucleus and the electrons are distributed around this. In the normal state of the atom, positive charge of the nucleus is exactly balanced by the negative charge of the electrons, so that the atom is electrically neutral. The overall radius of an atom (assumed spherical) is about 10^{-10} metres (one Angstrom), whereas the radius of the nucleus is about 10^{-15} metres (one Fermi). To get an idea of the relative sizes of an atom and its nucleus let us consider a hypothetical example. Imagine that the nucleus is of the size of a football, then an atom would be a huge sphere of radius around 15 km with nothing in between. Thus, an atom is essentially all empty space. A very important question that can now arise is the following:

If an atom is all empty space, then what provides it with the rigidity that is observed? This was a question which puzzled even Newton.

In a liquid or a gas, atoms are under constant motion and continuously colliding with each other. We know from everyday experience that if two bodies collide, part of the energy is used up in changing the shape and size of the objects. This is why in collisions between two steel balls, **kinetic energy** is not strictly conserved– some of it is lost and appears as heat. Newton thought that since atoms are under constant agitation, their properties should also change with time. He boiled water to increase the speed of collisions and studied its properties before and after boiling. To his surprise he found the properties of water before and after boiling to be the same, a fact he could not explain.

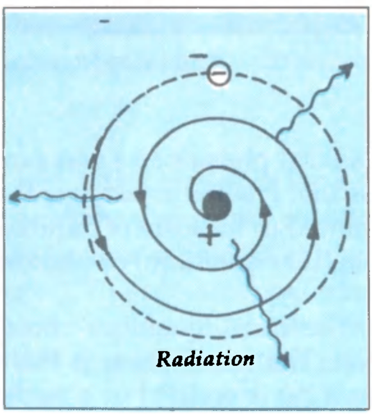
If we press hard on a stone or a wooden block from opposite sides, we cannot compress it. Now, since atoms are essentially all empty space, then how do these atoms acquire such great rigidity? This was one of the difficulties faced by the Rutherford model of the atom.

There was another basic difficulty with this model. This arose from the electrical nature of the nucleus and the surrounding electrons. If the electrons inside the atom are stationary, they would be pulled towards the nucleus by the strong **electrostatic force** and would fall into the nucleus. If we assume that the electrons revolve around the nucleus, as the earth revolves round the sun, then we get into another problem. An electron going around the nucleus in a circular orbit is moving under **acceleration** and James Clerk MAXWELL (1831-1879) proved that an accelerated electric charge would radiate energy and would gradually slow down and that an electron orbiting around the nucleus would drop into the nucleus within a time of about 10^{-10} second. Since matter is known to be stable, there must be something which prevents the electrons from falling into the nucleus. Thus, till around 1912, the stability of atoms seemed to be quite inconsistent with the known laws of physics.

Difficulties with the laws of classical physics began to be felt already around the beginning of this century. It was

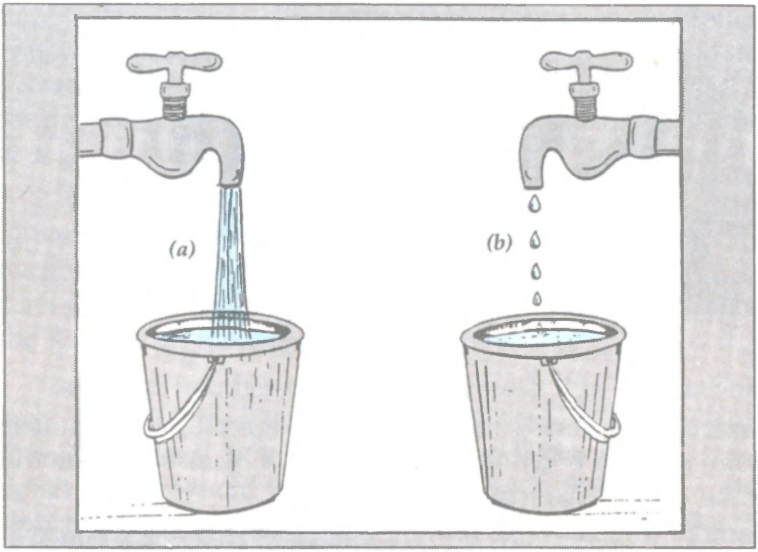
Very hard to compress

observed that one could not explain the radiation emitted from a heated body (strictly speaking 'a black body') on the basis of the existing laws. Though three laws governing the emission of radiation from a black body had been discovered, yet, in spite of various attempts, no connection between them could be discovered.



Orbiting electron falling to nucleus putting the stability of Rutherford atom in question

The radiations are essentially electromagnetic waves. Each wave has its **wavelength**. The number of complete cycles of waves per unit time is called its frequency. The shorter the wavelength, the higher is the frequency. In the early years of this century, Max PLANCK (1858-1947) succeeded in writing down a general expression for the **energy spectrum** of radiation emitted by a black body and showed that the above three laws were either special cases of this general expression or could be derived from it. However, to his great dismay, Planck found that he had to introduce a concept quite foreign to



Continuous flow(a) and quantum flow(b)

classical physics and was not reconciled to it for the rest of his life. He had to assume that electromagnetic radiation is emitted in the form of bundles, which are now called quanta (singular quantum) or photons.

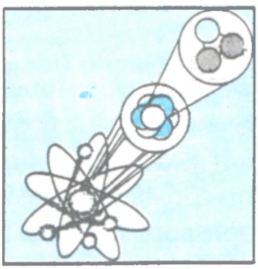
The word 'quantum' means a specified quantity or portion. The assumption is that the electromagnetic radiation (energy) is emitted or absorbed in a discontinuous manner rather than continuous manner. Take the example of pouring water. Water can be poured continuously from a container. It can also be poured drop by drop. In the first case, the flow of water is continuous, while in the second case it is discontinuous. It can be said that the drops are like quanta. In the case of radiation, any one of those little bundles is called a quantum of radiation.

A quantum of radiation carries an energy equal to the product of a constant and the frequency of radiation. This constant, denoted by h, is called Planck's constant and has a value of 6.625×10^{-27} erg second or 6.625×10^{-34} joule second. If we take **monochromatic radiation** of frequency, ν, and reduce its intensity gradually, under no circumstances can we obtain an energy less than $h\nu$. Low intensity radiation at a surface would imply fewer photons striking the surface in a given time. If electromagnetic radiation behaved like a **classical wave**, then on reducing the intensity of incident radiation, the **amplitude** (energy is proportional to the square of the amplitude) of the wave would decrease and could be made as small as one liked.

A black body emits radiation of all wavelengths. The energy of a photon of radiation having longer wavelength is smaller than the energy of a photon of radiation with shorter wavelength.

Like the velocity of light, c, which sets an upper limit on any physical velocity, h turned out to be a universal constant which sets a lower limit on action ('action' is defined as linear **momentum** multiplied by distance). This constant opened up entirely new vistas of physics and people soon realised that laws of classical physics were not enough to explain many natural phenomena.

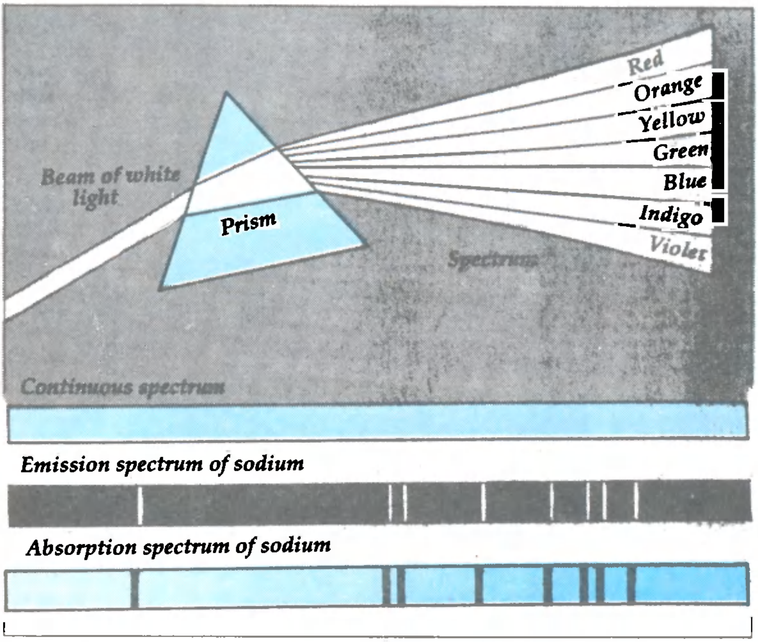
Bohr Model



Another problem which defied solution for a long time was the explanation of the observed spectra of elements.

Newton was amongst the first to demonstrate that light from the sun was composed of different colours. He demonstrated this by passing a beam of sun light through a prism. A century later Joseph von FRAUNHOFER (1787-1826), in more carefully performed experiments, observed some dark lines in the solar spectrum. Fraunhofer correctly identified them as absorption lines of atoms against a continuous background of solar radiation. Later, **emission spectra** of atoms of sodium, hydrogen and other elements were observed. These spectra were associated with distinct wavelengths, each element emitting a highly characteristic spectrum.

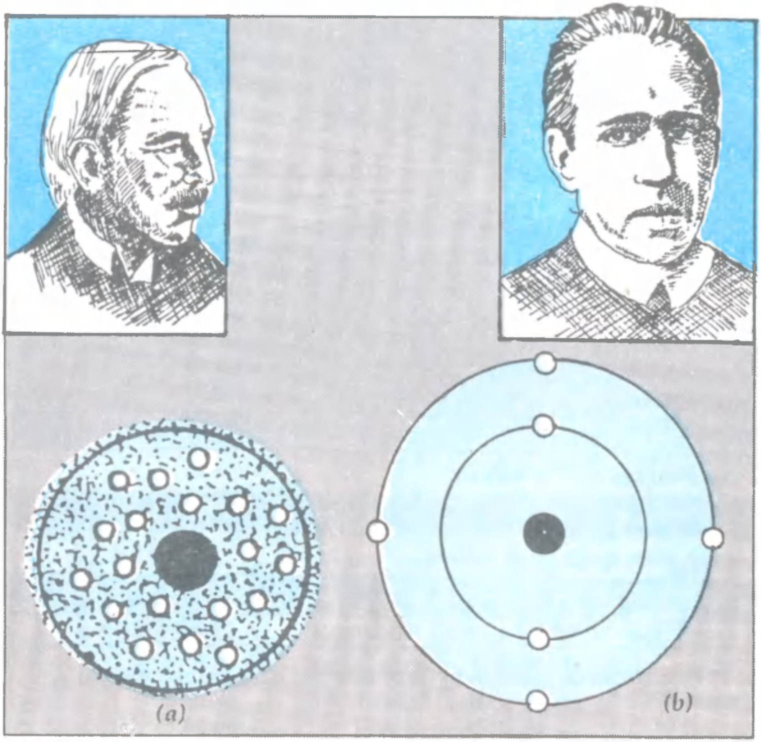
Johan Jacob BALMER (1825-1898) was the first to find a relation between the wave-numbers (reciprocal of wavelength) of the different lines of hydrogen. The different spectral lines of hydrogen atom could be grouped into several series. The different series carry different names. The series discovered by Balmer is named



Spectrum of white light (top) and that of sodium (bottom)

after him, whereas the other two series are called Lymen series and Paschen series. The particular form of expression for the wave numbers of lines in any given series could not be explained on more basic grounds. No clear understanding existed of the origins of these spectral lines and the observed relationships.

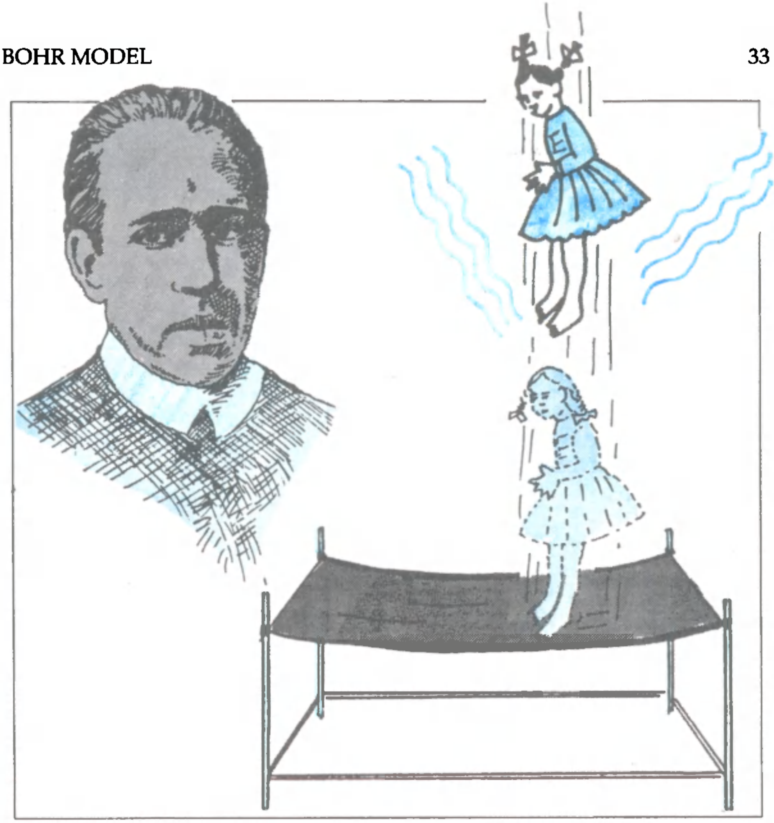
Niels BOHR (1886-1961) developed a planetary model for the hydrogen atom. However, in order to explain the hydrogen spectrum he had to introduce certain concepts which were totally foreign to classical physics and surprisingly involved Planck's constant, introduced into physics some years ago by Planck in dealing with the problem of **black body radiation**. Bohr started with the Rutherford model, according to which the entire mass of the atom is concentrated in the nucleus which is positively charged. Bohr pos-



Rutherford model (a) and Bohr model (b)

tulated that electrons move round the nucleus in well defined circular orbits or states. These states are referred to as 'stationary states'. When an electron moves in one of these orbits it does not radiate energy. An atom radiates only when an electron makes a jump from an orbit of higher energy to an orbit of lower energy. This energy is radiated in the form of a packet of energy, or a quantum. This quantum of radiation is called a photon. Bohr's model was highly successful in explaining the spectum of the hydrogen atom.

In a hydrogen atom the electron is bound to the nucleus and, therefore, the magnitude of its **potential energy** must exceed its kinetic energy. Since by convention we take the potential energy of a bound system as negative, the total



Niels Bohr and the energy radiation as electron falls to lower orbit

energy of an electron in a hydrogen atom is negative. The most stable orbit, the one with the lowest energy, called the ground state, corresponds to the lowest value of the **angular momentum**. In this orbit the energy of electron of hydrogen atom is – 13.58 eV (electron volts). As long as the electron is moving in this orbit it would continue to stay there without radiating. The electron cannot be pushed to a lower energy orbit because none exists. This accounts for the stability of the atom. The other orbits correspond to higher energies. The orbit with energy just higher than the ground state is at an energy of –3.40 eV. Hence the electron of the hydrogen atom, even when it suffers hard knocks with other atoms, cannot leave the ground state, so long as the energy imparted to it is less than 10.18 eV . This accounts for the great rigidity of the atoms.

Bohr on the basis of his theory, now succeeded in providing a generalised expression which explained all the spectral series of hydrogen atom. In fact, the different series of the hydrogen spectra were seen to be special cases of Bohr's general formula. This was a great achievement. In spite of the great success of Bohr's theory it suffered from some shortcomings. These were realised by Bohr himself, apart from Rutherford and others. The question was, how does an electron in a hydrogen atom, falling from a higher orbit, know where to stop so that a photon of corresponding wave-number is emitted?

Writing to Bohr, Rutherford pointed out, "There appears to me one grave difficulty in your hypothesis, which I have no doubt you fully realise, namely, how does an electron decide what frequency it is going to vibrate at, when it passes from one stationary state to the other? It seems to me that you would have to assume that the electron knows, before hand, where it is going to stop".

Bohr's theory, as was to be expected, was not immediately accepted, since it contradicted the concepts of classical physics. Even Lord RAYLEIGH (1842-1919), when asked to comment on the quantum theory of the atom, had the following to say: "In my young days, I took many views very strongly and among them that a man who has passed his sixtieth year ought not to express himself about modern ideas. Although I must confess that today I don't take this view quite so strongly, I keep to it firmly enough not to take part in this discussion". He was just over seventy at this time. The way out of this difficulty was found by Erwin SCHRÖDINGER (1887-1961) when he developed **quantum mechanics**.

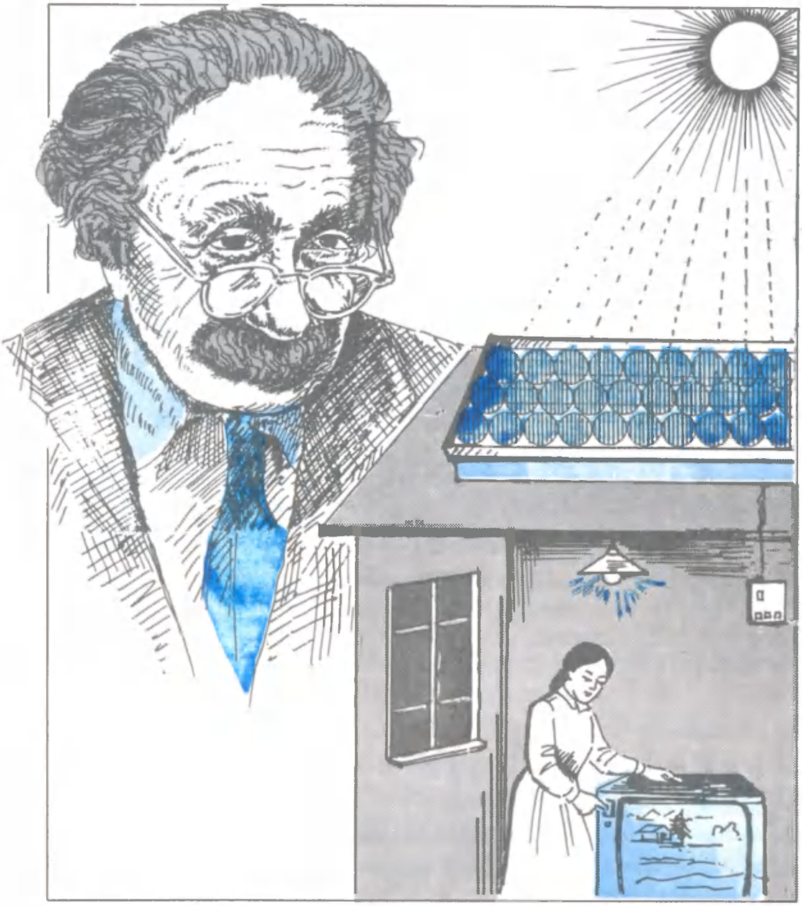
The quantum nature of electromagnetic radiation was introduced by Planck from his studies of black body radiation. This concept was so radically different from the concepts of

Schrodinger developed quantum mechanics that explained the jump of an electron to a particular orbit

classical physics that even Planck described this as 'an act of despair'. Bohr, talking about Planck, said, "In some sense it can be said that he (Planck) used the last forty years of his life, not to say fifty, to try to get his discovery out of the world". However, there were supporters of Planck's view about the quantum nature of electromagnetic radiation and amongst them was Albert EINSTEIN (1879-1955). Bohr's theory of hydrogen spectrum was based on this concept. Later two important experiments established the particle nature of electromagnetic waves.

Photoelectric effect

It was observed around 1900 by Philipp LENARD (1862-1947) that when ultra violet radiation falls on a metal surface it gets positively charged. It was interpreted later as being due to the emission of electrons from the metal surface when light of suitable frequency falls on it. This phenomenon is



Albert Einstein and the photoelectric effect

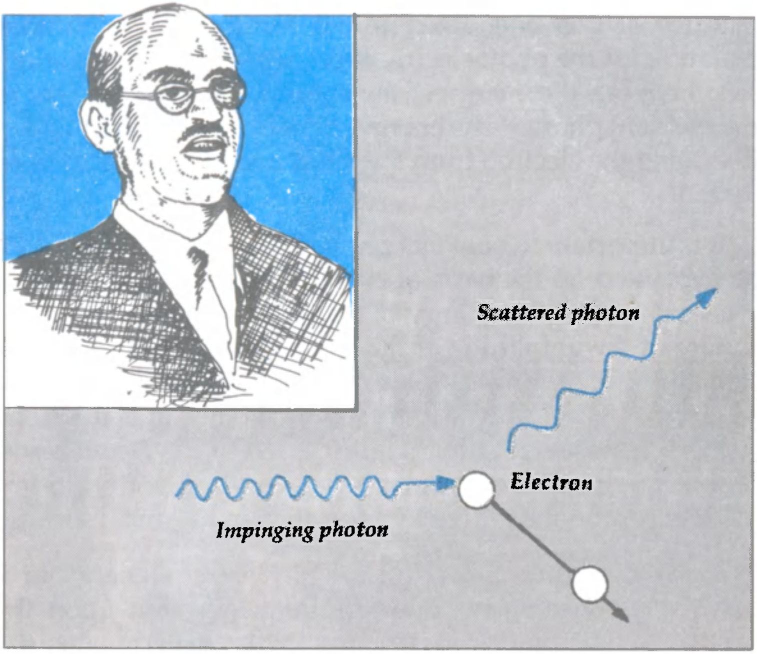
called the photoelectric effect. This effect was studied in detail by a number of workers, particularly Robert Andrew MILLIKAN (1886-1953). He established that the energy of the emitted electrons depended on the frequency of the incident radiation — higher the frequency, higher is the energy of the emitted electrons. He further observed that the number of electrons emitted per unit time increased with increasing intensity of incident radiation. Einstein explained all the features of this phenomenon and formulated his famous equation for the photoelectric effect, which shows a relationship between the energy of the emitted electron and that of the incident photon. The energy of the photon is expended in liberating the electron from the metal and imparting a velocity to it.

It is important to note that photoelectric effect cannot at all be explained on the basis of classical physics. According to classical theory, the energy of radiation depends upon the square of the amplitude of the wave and if the **intensity** of radiation is very low it would require considerable time for an electron to acquire enough energy to come out of the metal surface. However, in photoelectric effect, if the frequency is proper, irrespective of the intensity, photoemission starts immediately after the radiation is incident on the metal surface.

Further, according to classical physics, the energy of a wave does not depend upon its frequency (but upon the square of its amplitude), whereas in the experiments, the energy of the emitted electrons was observed to be directly proportional to the frequency. It is interesting to note that Einstein was awarded Nobel prize in the year 1921 for his work on photoelectric effect and not on any one of his other monumental works like special theory of relativity or general theory of relativity which completely changed our concepts of space and time .

Compton effect

The other experiment which clearly establishes the particle nature of light is the scattering of light by free electrons. Arthur H. COMPTON (1892-1962) observed that when X-rays are scattered by electrons there is a decrease in the wavelength of the X-rays, which is independent of the initial wavelength and is dependent only on the angle of scattering. This is referred to as Compton effect. Compton could explain this by considering the scattering process as an **elastic colli-**

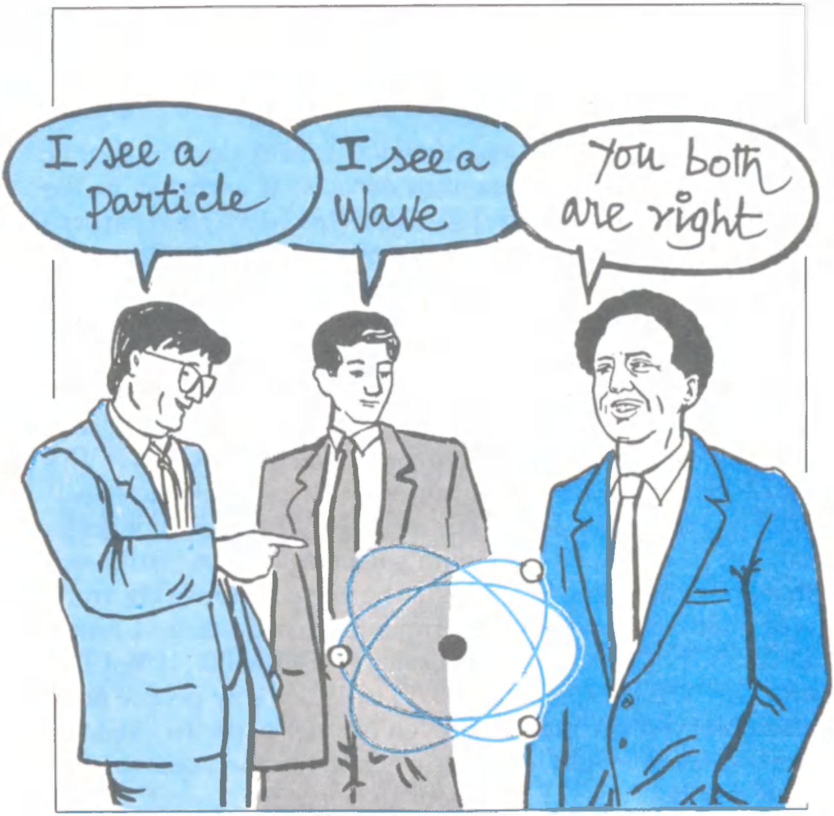


Compton observed the change in wavelength of X- rays (photons) due to scattering by electrons

sion between a photon and an electron. This experiment again established conclusively the particle nature of electromagnetic radiation and Compton was awarded Nobel prize for the work in the year 1927.

If we examine the work of great physicists in the area of optics, we find that at different periods of time the nature of light was always a point of controversy. Newton considered light as composed of corpuscles. Christian HUYGENS (1629-1695) developed his theory of reflection and refraction of light on the basis of wave theory. Augustin J. FRESNEL (1788-1827) and Fraunhofer experimentally demonstrated diffraction and interference of light and thought that they had conclusively demonstrated the wave nature of light.

In this century equally convincing experiments have been performed to demonstrate its particle nature. Thus, we seem



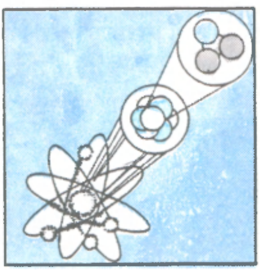
Louis de Broglie postulated dual nature of matter

to have run into a dilemma; light can show both wave and particle properties and what property one observes depends on the experiments performed. It will be appropriate to quote the great physicist of this century, Einstein, on this; "All these 50 years of conscious brooding have brought me no nearer to the answer to the great question 'What are light quanta? Now a days every Tom, Dick and Harry thinks he knows it, but he is mistaken".

The electron was discovered towards the end of the last century by J.J. Thomson. Its charge and mass were also subsequently measured. Bohr developed his theory of the hydrogen atom considering electron to be a classical particle with definite mass and charge and capable of possessing both potential and kinetic energies as well as angular momentum.

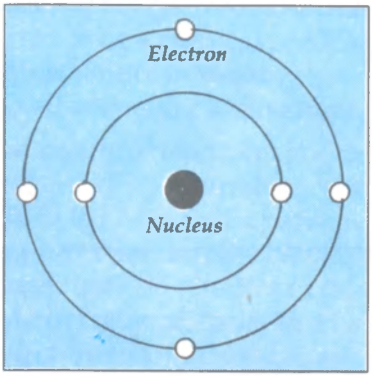
Following the discovery of dual nature of electromagnetic radiation (wave and quantum aspects) it occurred to the French physicist, Louis de BROGLIE (1892-1987) that particulate matter may also show wave properties. In 1924 he submitted his thesis for the Ph.D. degree entitled 'Studies in the Theory of Quanta' to Sorbonne University of Paris. In this thesis, de Broglie suggested that electrons should also behave like waves. He derived a relation which connects the wavelength with the linear momentum of the electron. The examiner of his thesis, the great French physicist, Paul LANGEVIN (1872-1946) in his conversation with Russian physicist A.F. IOFFE (1880-1960), said, "His ideas, of course, are nonsensical, but he develops them with such elegance and brilliance that I have accepted his thesis". The wave nature of electrons was later confirmed by experiments carried out by Clinton DAVISSON (1881-1958) and Lester H. GERMER (1896-1971) and G.P. THOMSON (1892-1975) in 1927. Now people have also observed **diffraction** of even heavier particles like neutrons and some light ions. The electron microscope, which is now a widely used instrument in scientific laboratories, is based on the wave nature of electrons.

Nuclear Structure



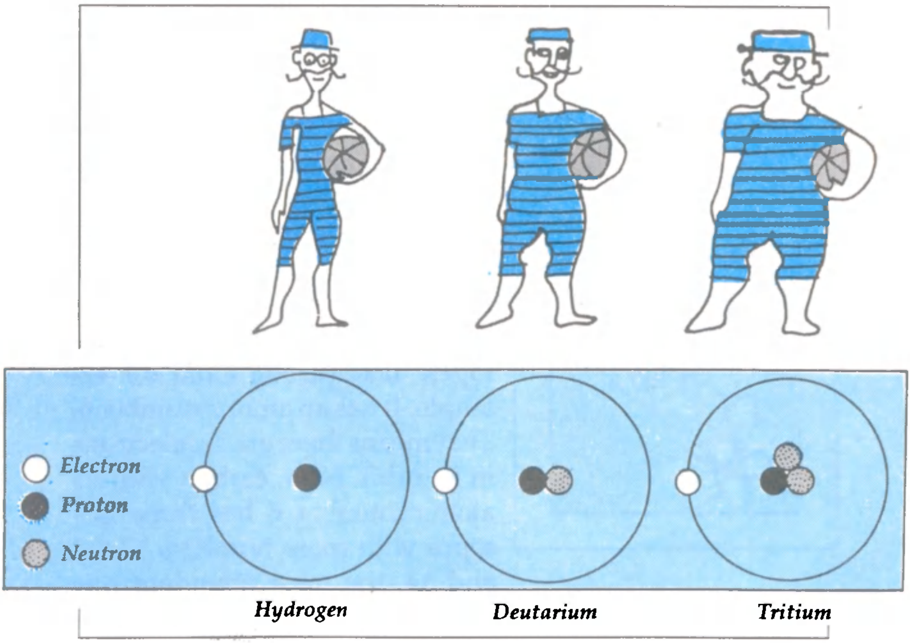
In 1886, Joseph GOLDSTEIN (1850-1930) discovered that like the cathode rays coming out from a perforated anode, certain rays also came out from holes bored through the cathode of the discharge tube. These were named canal rays. These rays were positively charged and a number of investigations were immediately undertaken to study their properties. It was observed that canal rays consisted of much heavier particles with various charge-to-mass ratios. Francis William ASTON (1877-1944) developed a 'mass spectrometer' to measure the charge-to-mass ratios of the different particles and was soon led to the discovery of **isotopes**. He found that the same chemical element could have different **mass numbers** and what the chemist measured as the atomic mass was an average of the masses of the different isotopes. Take carbon atom for example. It has an atomic number 6. That means there are six electrons in its orbit. Now, carbon with its atomic number 6 has three isotopes with mass numbers 12, 13 and 14, the most abundant one being the isotope with mass number 12. These isotopes are denoted by ^{12}C, ^{13}C and ^{14}C.

The mass number is written as a superscript on the left of the chemical symbol. Hydrogen has three isotopes and, because of their great importance, all the three isotopes have been given separate names. These are ^{1}H, ^{2}D and ^{3}T (D for deuterium and T for tritium).

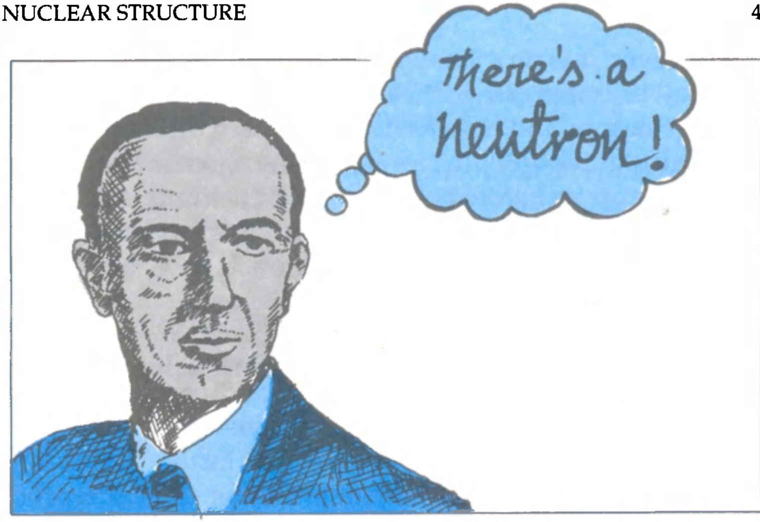


Common carbon atom

The nucleus of the hydrogen atom is made up of a lonely proton. It has a positive charge equal in magnitude to the negative charge of an electron and a mass about 1836



Isotopes of hydrogen



James Chadwick

times that of an electron. This name was proposed by Rutherford and is derived from the Greek word 'protos' which means the *first*, hydrogen being the first element in the Periodic Table.

In 1922, Rutherford, in one of his lectures to the Royal Society of London, proposed the possibility of existence of another particle having nearly the same mass as that of the proton but electrically neutral. Some neutral radiations were experimentally observed by Juliot CURIE (1900-1958) in France, but being unaware of the predictions of Rutherford, he could not interpret them correctly. It was Sir James CHADWICK (1891-1974) in Cambridge who, in 1932, identified these neutral radiations as the neutral particles predicted by Rutherford and was awarded the Nobel prize for this discovery. These particles were named neutrons. With the discoveries of these three basic particles namely, electron, proton and neutron, it was thought at one time that all the basic constituents of matter had been discovered. These constituent particles were termed as elementary particles.

However, it is now known that protons and neutrons are themselves composite particles. A number of other particles such as mesons and leptons have also been discovered. Present status of particle physics is in many ways similar to that of atomic spectra before Bohr, when a lot of information were available but which could not be satisfactorily explained for want of a proper theory.

According to our present ideas, an atom is composed of a positively charged nucleus with electrons moving around it. The nucleus is composed of neutrons and protons held together by **nuclear forces**. The number of electrons in the outer orbits is equal to the number of protons inside the nucleus and this number is called the atomic number. Chemical properties of atoms are governed solely by the electrons and, therefore, by the atomic number. The number of protons plus the number of neutrons is called the mass number.

It is obvious that the atoms of the same chemical element with a given value of the atomic number (proton number) can exist with different mass numbers. However, for the known elements, the number of isotopes that exists is usually small, mostly two or three. This implies that for a stable nucleus to form, the ratio of neutron number to proton number cannot take any arbitrary value. If the neutron number is more or less than what is required for stability, the isotope becomes unstable and decays by radioactive decay. If the number of neutrons is more than what is required for stability of the nucleus, it emits a *beta* - negative particle and if the neutron number is less, it emits a *beta* - positive particle. *Beta* - positive is a particle with a positive charge of exactly the same magnitude as that of the electron and having the same mass as that of an electron. It is called a positron. A positron is an 'antiparticle' of an electron.

So long as the number of protons (atomic number) remains low, for all stable nuclei, the number of protons is equal to the number of neutrons. As one moves towards the elements with higher atomic numbers, the neutron number increases more rapidly than the proton number.

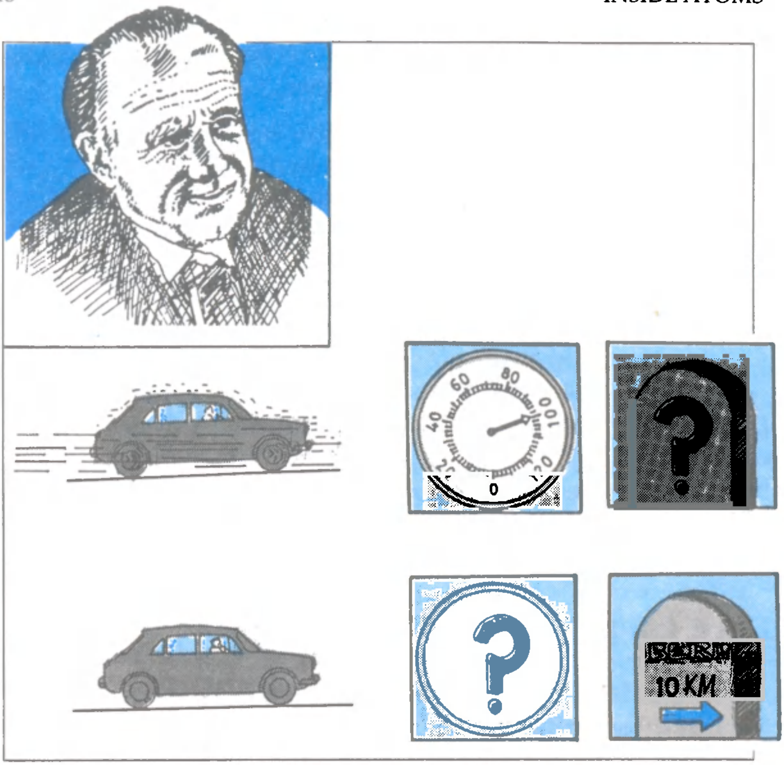
The heaviest nuclei (with proton numbers around 90), towards the end of the Periodic Table of elements, are found to be unstable. They are radioactive. Nature, on its own accord, tries to make them more stable. This happens as the nucleus emits charged particles. They can be either *alpha* particles or *beta* particles which come out spontaneously from a radioactive nucleus.

During the last few decades scientists have succeeded in producing elements in the laboratory with proton number exceeding 92. These are called transuranic elements. It has been conjectured that there should be an *island* of stability around proton number 114 and neutron number 184. So far scientists have not succeeded in reaching this *island*.

Uncertainty Principle

We have now learnt that the nucleus is composed of protons and neutrons and at the same time electrons (*beta* - negative particles), being emitted from it. From where do these electrons come?

Among the early models of the atom, before the discovery of the neutron, it was suggested that the nucleus should be composed of protons and electrons — the number of electrons inside the nucleus being equal to the difference of mass number and proton number. However, this model soon ran into trouble and one important difficulty was the discovery of the uncertainty principle by Werner HEISENBERG (1901-1976) in 1927. From very general considerations Heisenberg showed that it was impossible to precisely measure simultaneously the position and linear momentum of a particle. That means, any attempt to measure the position of a particle with exactness would cause an uncertainty in the measurement of its momentum, and *vice versa*. This inability to precisely measure simultaneously the position and linear momentum



Heisenberg who propounded the uncertainty principle

of a particle has nothing to do with the limitations of the measuring instruments and would arise even if we assume that our instruments are ideal and capable of precise measurements.

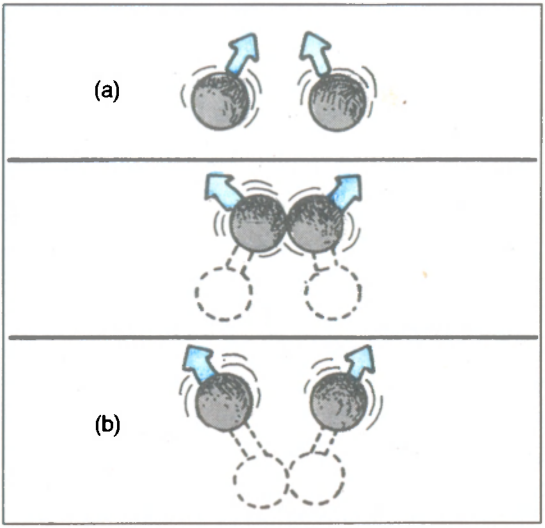
Heisenberg showed that the product of uncertainties in the simultaneous measurements of position and momentum of a particle is always greater than or equal to a certain constant which is symbolically represented by h. We get this constant when we devide Planck's constant by 6.28. This observation has made a profound impact on our understanding of structure of atom. Similar uncertainty also exists in the simultaneous measurements of energy and time. Now the question remains— can electrons exist inside a nucleus?

Suppose an electron exists inside a nucleus. We know that the size of a nucleus is roughly 10^{-14}metre and hence, according to the uncertainty relation, the uncertainty in the linear momentum of the electron will be nearly equal to 10^{-20}joule second. This implies an uncertainty in the kinetic energy of the electron to be of the order of 0.5×10^{-10}joule which is equal to 50 MeV (million electron volts). The binding energy of a nucleon (neutron or proton) inside the nucleus is 7-8 MeV. Hence, these electrons having a kinetic energy of the order of 50 MeV cannot be held inside the nucleus. Then how are electrons emitted from inside a nucleus? They are emitted from inside a nucleus because of nuclear transformation of neutron, where a neutron disintegrates into a proton, an electron and an antineutrino. Thus unlike protons and electrons, neutrons are also unstable particles.

It appears very reasonable to suppose that all protons are identical, means, all protons 'look alike' (if we could use this word for them) and have identical properties. Under identical conditions, any given proton would behave in the same way as any other proton. Similarly, all electrons would be identical and so will be all neutrons. However, though the particles say, protons, may be indistinguishable so far as their properties are concerned, yet, according to classical physics, we can identify each particle precisely and follow its course for all times.

Suppose two protons are approaching each other and then collide. By laws of mechanics one can follow the path of individual proton exactly after the collision and is able to identify each individual proton for all times, though the two are identical.

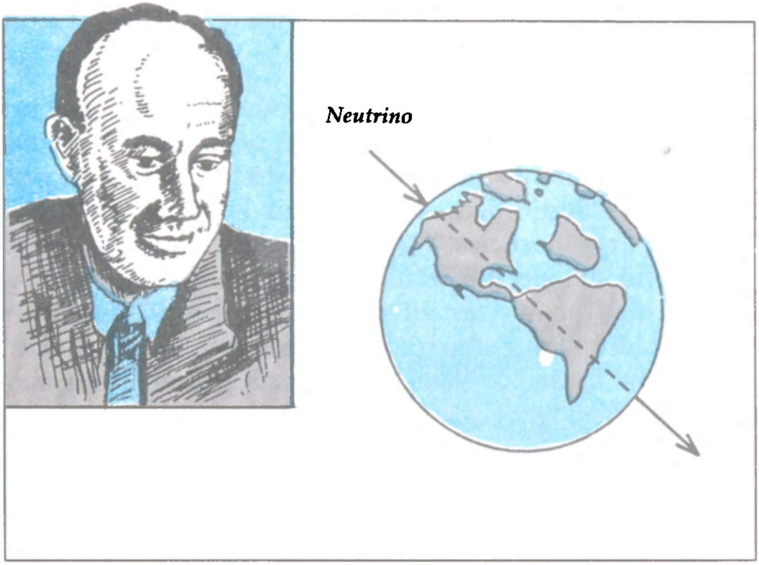
The situation becomes quite different when uncertainty principle is introduced into our consideration. When two protons are close together in a small region of space, their momenta become uncertain and hence also their kinetic energies. During collision one cannot, therefore, apply the strict laws of conservation of linear momentum and energy. The laws will apply, before and after collision, but not at the time of collision. Hence, we have no means of finding out the individual identity of the two protons and, therefore, the path of an individual particle cannot be followed. That is, when quantum laws apply, the concept of indistinguishability of particles acquires a much deeper and a 'truer' meaning.



Scattering of two protons (a) before collision and (b) after collision

Neutrino

While studying the *beta* decay of radioisotopes, one often measured the energy of the *beta* -negative particles emitted and found the *beta* particles to possess a continuous energy distribution ranging from zero to a certain upper limit. For example, in the case of *beta* decay of ^{14}C, the energy of *beta* particles ranges from 0 to about 140 keV. This implies that electrons emitted by different nuclei of ^{14}C atoms possess different energies. Some were emitted with a fairly large energy, while some others with a very small energy, giving rise to a continuous energy distribution. This seemed to violate the well established law of conservation of energy, since the energies of ^{14}C and ^{14}N were correctly assumed to



Enrico Fermi coined the name neutrino for a particle that can pass through the earth without interaction.

be well defined. In 1931, Wolfgang PAULI (1900-1958), a great theoretical physicist, suggested that in each *beta* decay, a third particle is also emitted and the energy available in ^{14}C going to ^{14}N is shared between the electron and this new particle. This suggestion could then account for the observed continuous energy spectrum of the *beta* particles.

This new particle, called antineutrino, is supposed to be electrically neutral, has zero mass and interacts very weakly with matter. An antineutrino or its antiparticle, the neutrino, could pass right through the earth without interaction. This name neutrino meaning the little neutron was suggested by Enrico FERMI (1901-1954).

It was only in 1956 that the existence of neutrinos was experimentally verified by Frederick REINES (1918-) and

Clyde COWAN(1919-). In 1995 Reines was awarded Nobel prize for his work.

We have learnt about some elementary particles and how they were discovered. It is useful to pause here and know about the different kinds of interactions between these particles. Surprisingly there are only four kinds of interactions between these particles. We already know about the gravitational and the electromagnetic interactions. The other two are: 'strong' or nuclear interaction and 'weak' interaction. There is a fifth force which acts between **quarks**, the constituents of the nucleons (name for protons and neutrons taken together). Its agent is **gluon**.

Gravitational Interaction.

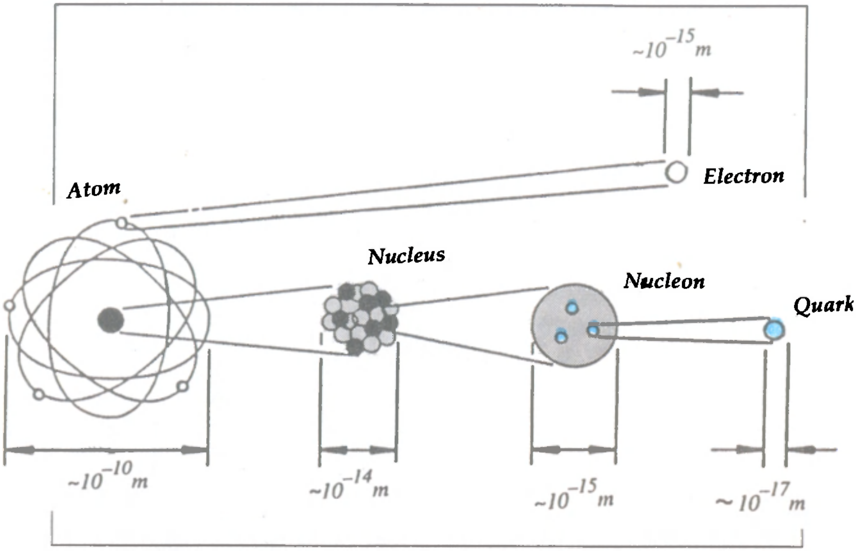
For elementary particles, this is the weakest of the forces. It is proportional to the product of the masses of the interacting bodies, and inversely proportional to the square of the distance between them. This means that if the product of masses of two bodies increases, the gravitational force between them also increases. On the other hand, if the distance between them increases, say, 2 times, the gravitational force decreases 4 times. Similarly, if the distance increases 3 times, this force will decrease 9 times.

The gravitational force between two protons separated by a distance of a nucleon diameter (10^{-15}metre) is $2x10^{-34}$newton. Here, newton is the unit of force.

Gravitational force is a universal property of all matter and is always attractive. It extends over all space. We say that the range of gravitational force is infinite. Just as a photon is a quantum (particle) of electromagnetic radiation, or an agent of electromagnetic field, 'graviton' is the agent of gravitational field. Graviton, though not yet experimentally discovered, is conjectured to have zero (rest) mass and travels with the velocity of light.

Electromagnetic Interaction

Most of the forces we encounter in nature are electromagnetic in character. The atoms, molecules and other complex structures arise because of these forces. They can be of different types, electrostatic (as between two charges), magnetostatic (between magnets), electromagnetic (as between currents) or through electromagnetic radiation. As we know, this force can be attractive as well as repulsive. The range of this force is also infinite. Photons are the quanta of electromagnetic radiation. They have zero (rest) mass and travel with the velocity of light.

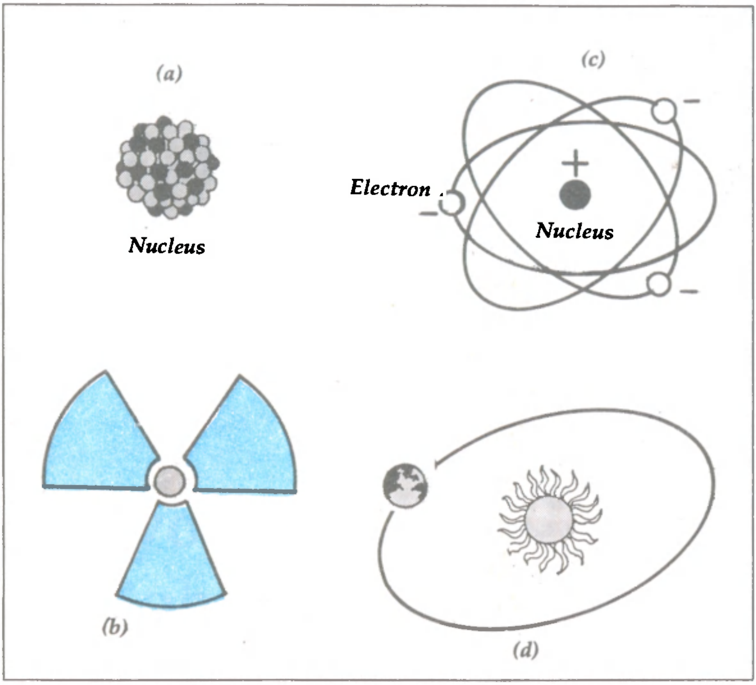


Nuclear dimensions

The electrostatic force between two protons separated by a nucleon diameter (10^{-15}metre) is found to be 230 newtons. So, the ratio of electrostatic force to the gravitational force between two protons is nearly 10^{36}, a huge number. Therefore, when electrostatic forces come into play, one can totally forget about the gravitational force.

Nuclear Interaction

The force which binds protons and neutrons inside a nucleus is called the nuclear force. This is attractive and about 100 times stronger than the electromagnetic force. It is of short range, that means the force is important only within distances of the order of nucleon dimensions, and is zero beyond this distance. From this property of the nuclear force, the Japanese physicist Hideki YUKAWA (1907-1981) concluded that the 'agent' responsible for this force must have a mass of about 300 electron masses.This particle was later named as 'meson'



Four fundamental forces; (a)Strong force: binds the nucleus; (b) Weak force: radioactive decay; (c) Electromagnetic force: binds the electrons to nucleus; (d) Gravitational force: holds together all matter in the universe

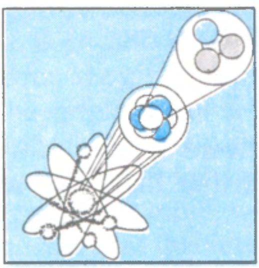
and represented by the symbol π. This particle was later detected experimentally.

Mesons can be positively charged, negatively charged, or be electrically neutral. These mesons are also called pions. They are unstable and decay into other elementary particles such as muons, muon-neutrino and muon-antineutrino. For instance, the positive pion decays into positive muon and muon-neutrino, whereas the negative pion disintegrates into negative muon and muon-antineutrino. These neutrino and antineutrino are different from the electron-neutrino and electron-antineutrino.

Weak Interaction

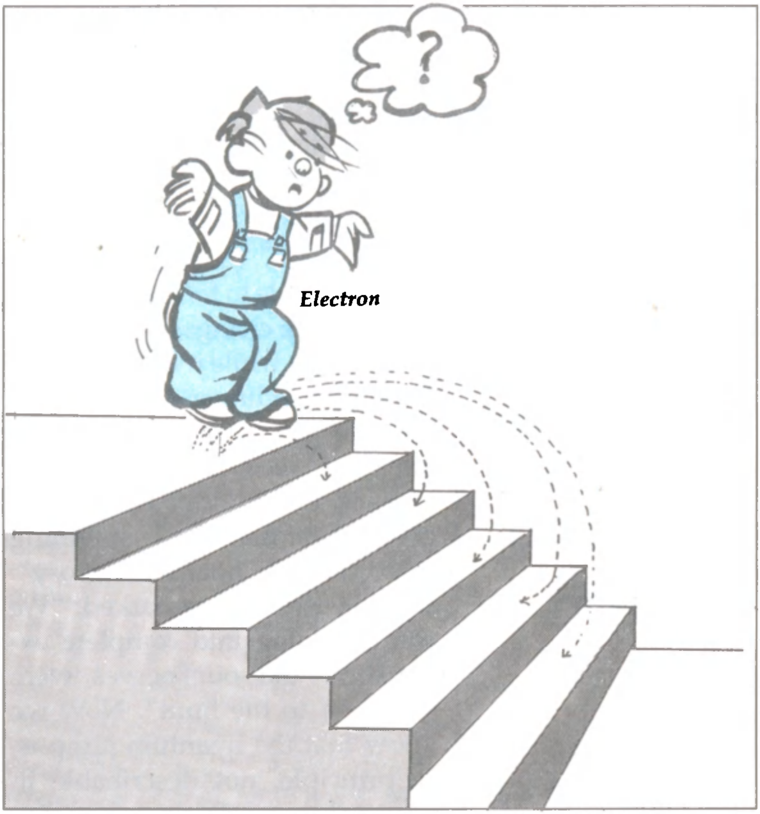
A new force was proposed by Fermi around 1930 to explain *beta* decay of nuclei. This force is about 10^{-7} times weaker than nuclear force and is called 'weak interaction'. The decay of the neutron and the muon arises because of this force. The 'agents' responsible for this force are called 'Intermediate Vector Bosons' and are denoted by W^+, W^- and Z^0.

Beyond Bohr



Two basic difficulties of Bohr model troubled the early workers most. One difficulty was — how to describe the electron when it is making a jump from one orbit to another? The electron jump may be very fast, but at least, in principle, one should be able to follow the trajectory and the changes in energy of the electron while it is making the jump. Schrodinger at one time said, "If these damned quantum jumps, indeed, are retained in physics, I will not be able to forgive myself that I had something to do with the quantum theory". Even Heisenberg remarked, "We were slipping into complete exhaustion and our nerves were stretched to the limit". Now we know that the quantum jump is, in principle, not describable in physical terms. But this was not clear earlier.

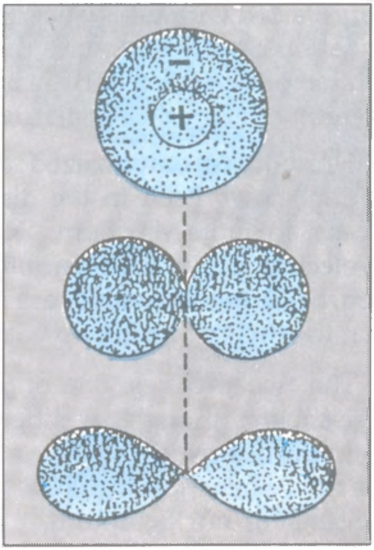
The other difficulty was – while making a transition from an orbit of higher energy to one of lower energy, how does an electron decide at which intermediate level to stop, so that a photon of corresponding frequency (energy) can be emitted? In resolving these problems Schrodinger and Heisenberg played major roles. Though the basic concepts devel-



Where to stop after the jump

oped by Schrödinger and Heisenberg were differnt, it was proved, in the ultimate analysis later, that these two approaches are equivalent.

Following de Broglie's idea of wave nature of particles, Schrödinger developed an equation to describe the wave aspect of particles. This is now called the Schrödinger equation. This equation can be used to describe the wave nature of particle. Schrödinger said that the orbit of an electron must contain a whole number of wavelengths. In case, the circumference of an orbit divided by the wavelength of electron's matter wave, does not give a whole number, the electron cannot maintain itself in that orbit. The electron then moves to an orbit where the above condition is satisfied. Max BORN (1882-1970) first gave the correct physical interpretation to the solution of Schrodinger equation. He derived a relation to show the probability of finding the particle in a unit volume about a **space point**. According to this relation one cannot talk of the exact location of a particle but only of the probability of finding it in an element of volume about a point in space.



Probability distribution can have different shapes

Thus, an electron simultaneously exists everywhere since its wave property is defined at all space points. When we try to make a measurement to locate an electron in a given region of space, we can only predict the probability of its being there. Max Born also showed that the probability of finding an electron at a given point in space is proportional to the square of the amplitude of electron's matter wave. This probability distribution, known also as the cloud of probability, can have different shapes for a given energy. The probability of finding the particle is more, where the cloud is dense. One can thus easily see that this interpretation is fully consistent with the Heisenberg's uncertainty relation.

An alternative approach of describing atomic processes, consistent with de Broglie principle of duality of matter, was almost simultaneously developed by Heisenberg. However, unlike Schrodinger who began with a wave picture, Heisenberg started with the particle or corpuscular description. His equation closely resembles the Newtonian equation for the motion of a classical particle but makes use of **matrices**. It is, therefore, referred to as matrix mechanics.

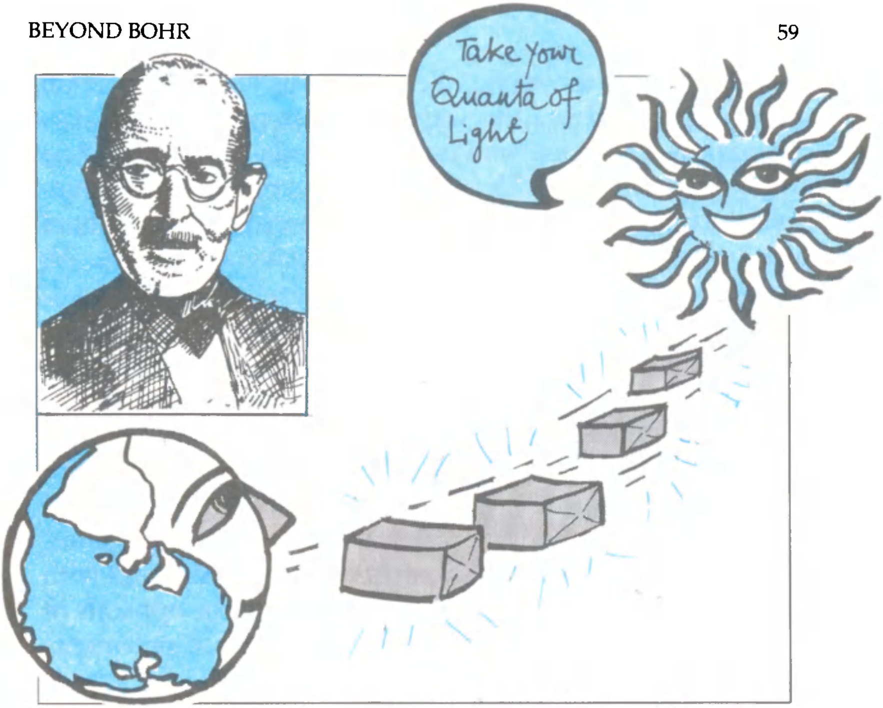
Heisenberg emphasized the element of discontinuity which shows itself in the discreetness of spectral lines of atoms. To quote Max Born, "Heisenberg rejected the concept of electron orbits with definite radii and periods of revolution, because these values are not observable and demanded that the theory be built up with the help of matrices".

The two theories, one of Schrödinger and the other of Heisenberg, though so different in approaches, correctly yield the observed spectrum of hydrogen atom. However, at the time when these developments were taking place, neither Heisenberg nor Schrödinger appreciated each other's approach. In a letter to Pauli, Heisenberg wrote, "The more I ponder about the physical part of Schrödinger theory, the more disgusting it appears to me". Schrödinger on the other hand freely published his response to Heisenberg's theory: "I was discouraged if not repelled".

In spite of the apparent dissimilarity between the two approaches, it was soon proved that they are equivalent and give identical results in all cases.

We know from experience and also from classical physics that particles and waves are two totally different entities. One can precisely specify the coordinates of a particle in space at any particular time. Its properties are specified by mass, momentum and energy.It can also carry an electric charge and, may be, also a magnetic moment.

On the other hand, an ideal monochromatic wave at any given instant of time, extends over all space from plus infinity to minus infinity. It is characterized by two parameters, namely, wavelength and frequency. It is described by the wave equation which is very different from the equation for a particle.



Max Planck introduced the concept of quantum of radiation

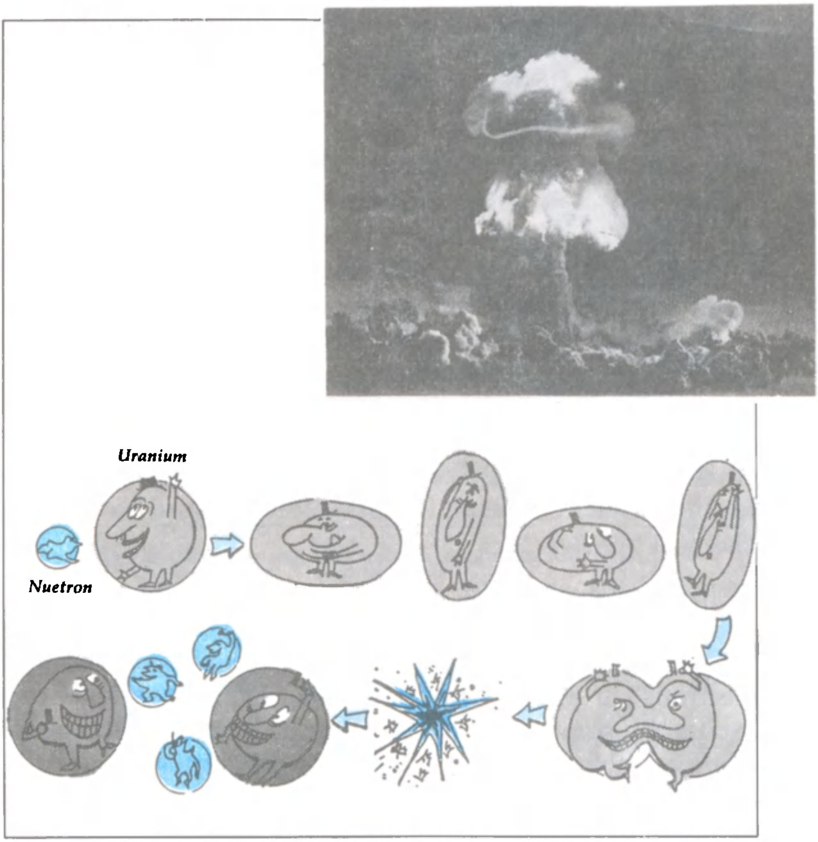
When, in 1900, Planck first proposed that electromagnetic waves also behave like quanta, the concept was so radical and irreconcilable with all that was known earlier, that even Planck spent the rest of his life worrying about it. The discovery by de Broglie that matter can also behave like waves, though a direct consequence of Planck's discovery, was even harder to reconcile. Since all our concepts and languages have developed from observing nature on a **macroscopic scale**, there is no way we can describe these seemingly contradictory properties in a consistent way, except through mathematics.

From wave nature of particle, de Broglie showed that the wavelength of an object is directly related to the Planck's constant and inversely proportional to the mass and velocity of it. In other words, the larger the object or the faster it is moving, the shorter the wavelengths of its wave. For a small particle like electron, the wavelength associated with it is comparatively long. Even Planck's formula has both particle and wave parameters. These are amongst the strangest equations in physics since they connect parameters associated with two entirely different entities, particles and waves. We must note here that this dual nature of matter exhibits itself clearly only for elementary particles.

Bohr devoted considerable time to resolve this paradox and came up with his *principle of complementarity*. According to this principle, two opposite statements (for example, wave and particle aspects) need not be contradictory, but are complementary This principle is perhaps most significant and revolutionary concept of modern physics. In Indian (generally Eastern) philosophy such situations have been dealt with from very early times and it was realized that the opposite of a deep truth could also be true. We come across statements like *Nirguna Brahma* (non-space time universe) and *Saguna Brahma* (space time universe) to denote the same reality. Looked at casually, these two are contradictory terms.

The development of another equally revolutionary idea in our understanding of nature started around 1905 and is the creation of essentially a single individual, Einstein. Till all these centuries, space and time were considered separate and independent entities. Time flowed at a constant rate and all physical phenomena took place in time, in no way affecting it.

Towards the end of the last century,a number of observations had been made which established that unlike velocities of all physical objects, velocity of light was independent of the velocity of the source or of the observer. This was a most unexpected result. This result could not be explained on the basis of classical theory, and puzzled Einstein from a very early age. He finally resolved this difficulty and developed, what is now known as the 'special theory of relativity'. This theory has completely changed our concepts of space and time. Einstein showed that space and time are closely linked and affect one another. Only for velocities much smaller than the velocity of light can one forget about this linkage and treat them as independent. Another major consequence of this theory was to establish the equivalence of mass and energy. Einstein obtained the now famous equation $E = mc^2$, where, E is the energy, m the mass and c the velocity of light. Among other things, it succeeded in explaining the observed loss of

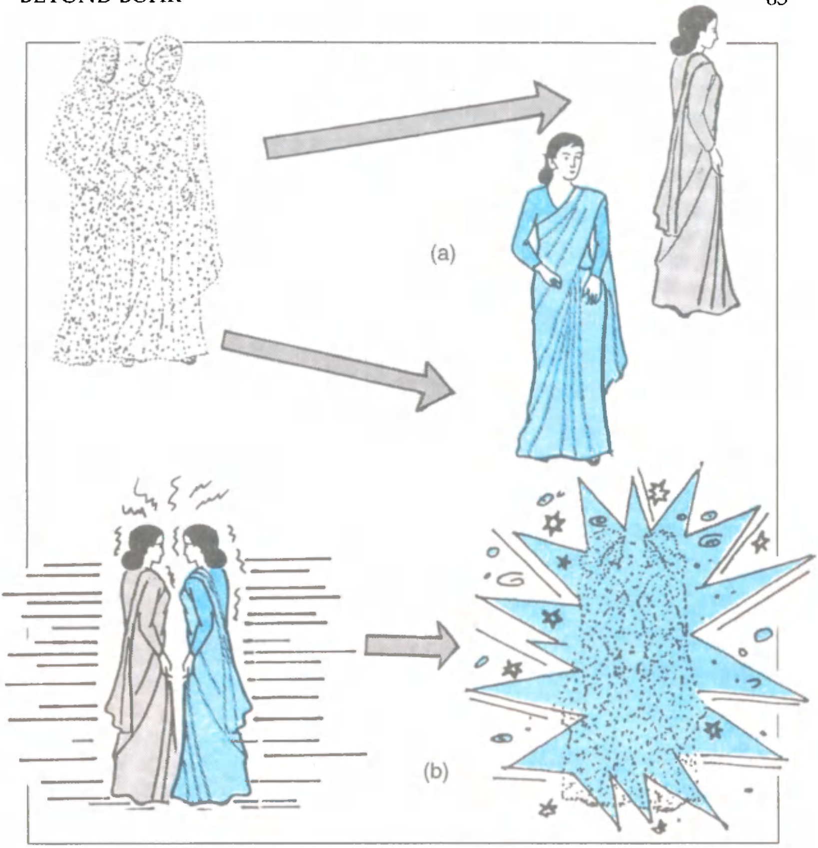


(a) Devastating atomic explosion–demonstration of Einstein's mass-energy relation; (b) A neutron bowls into the nucleus of heavy weight Uranium 235, makes it unstable and finally split into two with the release of energy and three more neutrons mass when nucleons combine to form nuclei, and also the energy generation in stars due to **fusion** of light nuclei.

It is now almost a requirement that any good physical theory must conform to the principles of 'special theory of relativity'. The equation developed by Schrodinger does not conform to the requirements of 'special theory of relativity' and, therefore, one would expect it to break down for elementary particles moving at very high speeds, that means speeds close to the speed of light.Around 1928, Dirac succeeded in formulating an equation for the electron which conforms to the requirements of the 'special theory of relativity'.

However, it led to some queer results. The electron represented by his equation also had another attribute, which we call spin. The spin of an electron is its intrinsic property and the angular momentum associated with the spin has a magnitude $(1/2)\,\hbar$. Further, what is more striking is that this angular momentum vector can point only along two directions which are normally referred to as 'up' and 'down'. Thus, we see that the spin angular momentum of an elementary particle is a purely quantum mechanical property with no analogy in classical mechanics. Dirac further found that his equation led to the existence of negative energy states even for free particles, a result which is totally absurd according to classical physics.

To get over the difficulty of these negative energy states, Dirac assumed that these negative energy states are all filled by electrons. One refers to this as 'the sea of negative energy electrons'. If an electron from this negative energy sea is excited by some external radiation or particle with suitable energy so that it comes out into a positive energy state, then a 'hole' is left behind in the negative energy sea. This hole behaves like a real electron but with a positive charge. Such a positively charged electron is called a positron. Thus, when a positron is produced, an electron is also simultaneously created and this process is referred to as pair production. We refer to the positron as an antiparticle of the electron and *vice*



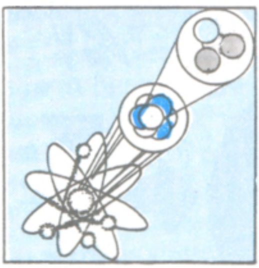
Pair production (a), and annihilation of matter (b)

versa. One needs a photon of energy of at least 1.02 MeV to create an electron-positron pair.

When a positron meets an electron, the electron - positron pair is annihilated and electromagnetic radiation is emitted. One can easily verify that in such an annihilation of two particles, two or three photons will be emitted. One photon can never be created, since this would violate the law of conservation of (linear) momentum.

Positrons were discovered in cosmic rays by Carl David ANDERSON (1905-) in 1932. Positron is one of the few particles which was predicted from theory before it was actually experimentally observed. As Heisenberg put it, "I think that this discovery of antimatter was perhaps the biggest of all the big jumps in our century". Positrons do not normally exist in nature (as do electrons), but now positron sources can readily be obtained. These antiparticles of electrons have found many applications in medicine and technology.

Exotic Atoms

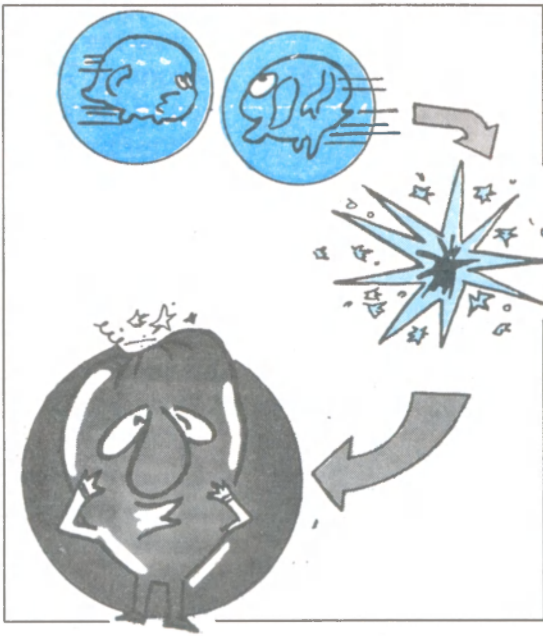


About ninety two elements are found to exist in nature. Elements beyond atomic number 92 have been produced in the laboratory and the Periodic Table now extends up to atomic number 106. The relative proportion of elements found on the earth's crust and that of atoms in stars, as determined by the study of their spectra, are entirely different. In stars, hydrogen dominates, followed by helium and with small proportions of other elements. One question can obviously arise in one's mind as to how the heavier atoms came to be formed. The story of the formation of heavier elements is quite interesting.

Stars have been classified into various categories, but we cannot go into these details. Consider a typical star, say, our sun. In the interior of the sun, temperatures are in the range of approximately 10^8 degree celsius which gradually drop to nearly 6000 degree celsius on its surface. The mass of the sun is nearly 2×10^{30} kilograms and its radius nearly 6.96×10^5 kilometres, giving a density of the order 1.4×10^3 kilograms per cubic metre, which is slightly higher than the density of water. In the core of the sun, because of the high temperature and pressure, nuclear reactions take place in which four protons combine to form a helium nucleus. One possible cycle of reactions is proton - proton cycle.

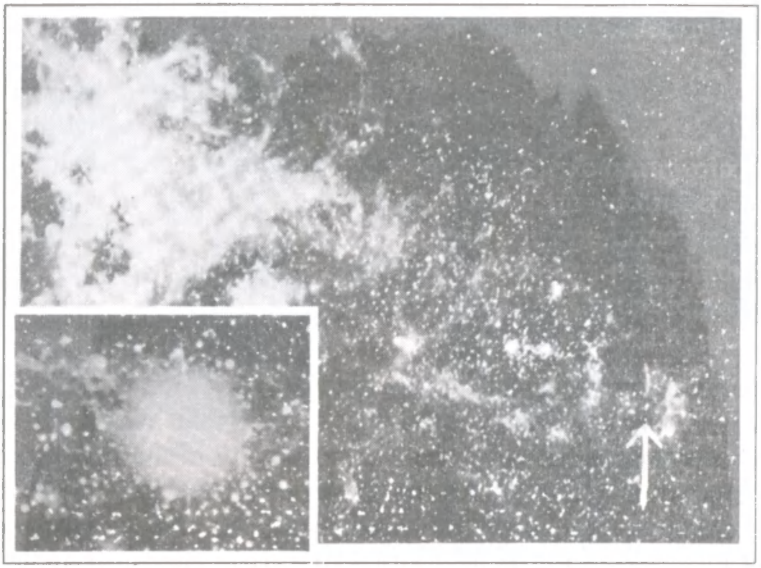
This cycle dominates in stars with comparatively low temperatures (nearly 10^7degree celsius) and large hydrogen content. In spite of the high density of the core, it takes almost $3x10^9$ years for this cycle to complete. These nuclear reactions in the sun produce energy which is nearly $4x10^{25}$ joules per second. This amounts to a loss of mass of the sun close to 10^9 kilograms per second.

As hydrogen burns out and helium begins to dominate, the rate of generation of energy decreases and the star begins to collapse under its own gravitational force. In this process the temperature rises and other nuclear reactions involving heavier nuclei begin. Over a period of billions of years that stars have existed, heavy nuclei have been formed inside their interiors. Nuclei with atomic number more than 92, being unstable under spontaneous fission and radioactive decay, do not survive for long in the stellar interior.



Nuclear reaction in the sun—two isotopes of hydrogen collide to form a heavier helium atom with the release of energy

Under certain conditions a star may explode. If such an explosion occurs near



The Large Magellanic Cloud and (inset) the Supernova of 1987

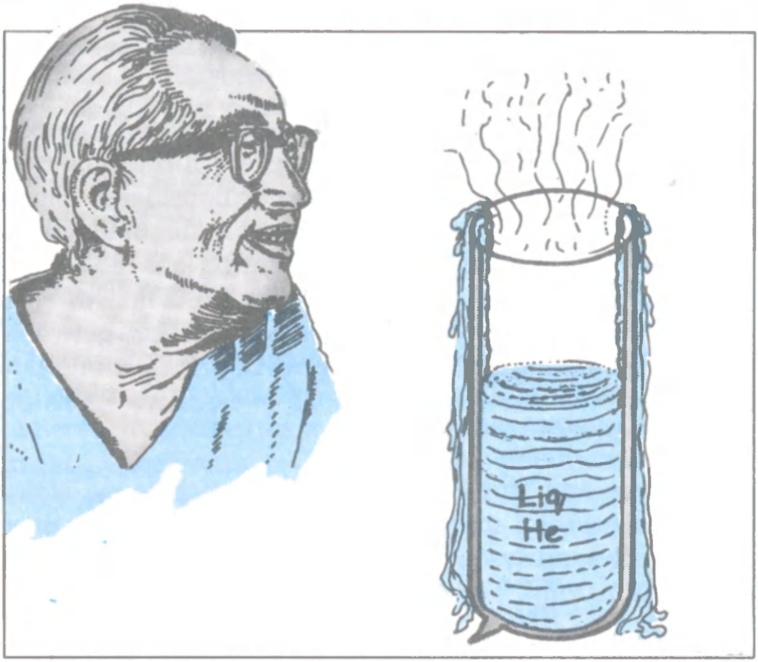
our solar system, the brightness of the star suddenly increases many folds and then gradually dies down. Such events are called supernova. Remnants of one such explosion is still visible in the night sky with the help of a small telescope and is the 'Ring Nebula'. Another explosion was observed in the southern hemisphere of the sky on 23rd Feb. 1987. In these explosions, stellar matter is dispersed in space and may condense to form cold bodies. It has been shown that a cold body larger than Jupiter would be unstable. The composition of elements in these cold bodies, though they are remnants of dead stars, is entirely different from that of the stars, since most of the gases, particularly, helium and hydrogen, escape into space. Thus, we can say that the atoms of which our bodies and the rest of the things around us are made, were cooked in the stars.

Fermions and Bosons

We have seen that electrons and their antiparticles positrons have spin, possessing an intrinsic angular momentum of $(1/2)\hbar$. It has been observed that protons and neutrons also have spin of $(1/2)\hbar$. It is found that particles with spin having odd multiples of $(1/2)\hbar$, in some ways, behave similarly. This class of particles is referred to as 'fermions', after the great Italian physicist Enrico Fermi.

Pauli observed that in the state of an atom specified by a given set of quantum numbers no more than two electrons can be accommodated. If an atom has more than two electrons they have necessarily to go to states with different quantum numbers. This is referred to as *'Pauli's exclusion principle'* and has been used to explain the arrangement and the properties of different elements in the Periodic Table. This is one of the major achievements of quantum theory of matter.

It has also been observed that if two electrons, or an electron and a positron, or two protons and two neutrons form a composite system, they no longer behave like fermions. Even the properties of light quanta are entirely different from those of fermions. These particles and photons are associated with spins zero or integral multiples of $\hbar$ and form a class of particles which are referred to as bosons, after the great Indian physicist S.N. BOSE (1894-1974). These particles, under certain special conditions can exhibit properties which would normally be unimaginable. They account for the phenomena of LASER (acronym for Light Amplification by Stimulated Emission of Radiation), **superconductivity** and **superfluidity**. Unlike in the case of fermions, any number of bosons can go into the ground state, and larger the number that has gone into this state, greater is the probability for other particles to go into that state.



S. N. Bose whose work explained the unusual behaviour of liquid helium

Exotic Atoms

Fundamental particles like the pions, muons, positrons and others exist in nature. The properties of the muons are found to be similar to those of electrons, except that they are about 200 times heavier and also that they are unstable and have a half-life of about 2.2 microseconds (1 microsecond = one thousandth of a second). It is reasonable to ask, can an electron be replaced by a negative muon in an atom?

Such muonic atoms have been produced in the laboratory. Muon being about 200 times heavier than the electron, the radius of the muon orbit in the ground state is smaller by almost a factor of 200 and energy of the ground state proportionately much higher. Transitions between lower levels of muonic hydrogen will thus generate X-rays. However, since negative muon is an unstable particle, the life time of such an atom would be about 2.2 microseconds.

One can also form molecules that have an electron replaced by a negative muon. A muonic molecule formed of two heavier isotopes of hydrogen can also be considered. Since the orbit of the muon is two orders of magnitude smaller than the corresponding electron orbit, the nuclei are held close together and nuclear reaction becomes possible. Muonic molecules can thus catalyze nuclear fusion reactions between hydrogen isotopes at low temperature. In principle one can also form atoms with negative pions or negative keons or even antiprotons.

A positron and an electron can also form a bound state. When a positron and an electron come close to each other they may form a bound system (like a hydrogen atom,) known as 'positronium atom'. The binding energy of the positronium atom in the free state is 6.8 electron volts. Unlike the case of a hydrogen atom, a positronium atom has two ground states (singlet and triplet), depending upon the spin alignment of the electron and the positron constituting the positronium. As positron and electron are antiparticles to each other, a positronium exists for a short period of time.

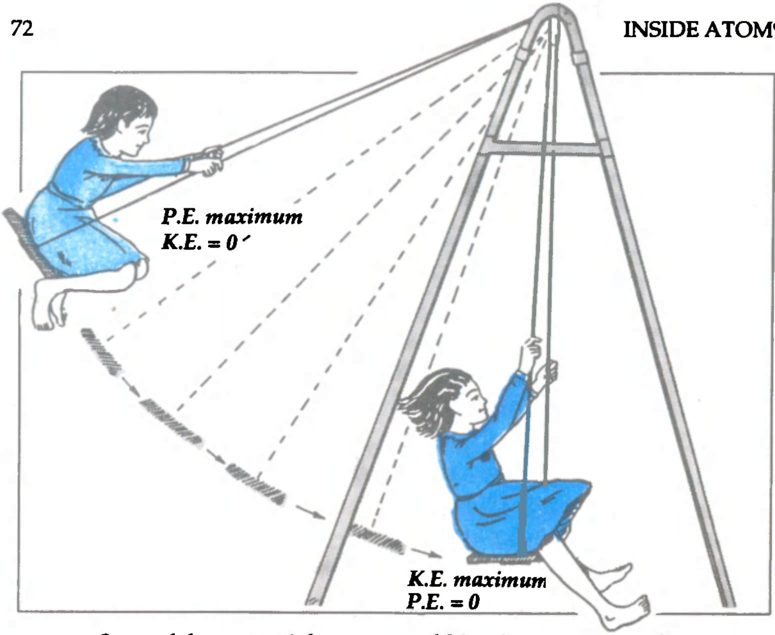
Conservation and Symmetry

Suppose a child is playing in a room with some marbles. Say, the number is twenty. The mother comes into the room after sometime and finds that there are only 10 marbles left with the child. She is worried about as to where the marbles have gone. The mother notices a closed box lying nearby which the child will not permit her to open. There is also a glass of milk, from which the child has not even taken a sip, but its level is more than what it was when she had given it to the child. Further, the box appears to be heavier. The mother can find the number of marbles in the glass of milk by finding out the rise in the level per marble and then measuring the rise in level in the child's glass. The number of marbles in the box can also be determined without opening it if she knows the mass of the empty box and again weighs it with the balls inside. The difference in mass divided by the mass of a single marble will give the number of marbles inside the box.

In this simple example, we notice that the mother expects the number of marbles to remain the same. We say that the number of marbles is conserved. However, under different situations there are entirely different ways of finding out the number of marbles. In one case, simple counting will do, whereas in other cases we have to either measure the mass or measure the volume. These latter two parameters are physically quite distinct and their methods of measurements are also totally different.

It was observed quite early that, when any physical or chemical process occurs, certain quantities are conserved. It was found that, in a physical process, quantities that we now call energy, linear momentum and angular momentum are conserved. Take the case of energy. When a ball is dropped from a height, it gains speed as it drops. The energy due to motion, which we call the kinetic energy, increases continuously. This increase must imply that some other form of energy is decreasing. As you know, it is the potential energy which decreases as the ball falls. Since the ball is falling through air, it transfers some of its energy to the air molecules which eventually will heat the gas. The same is true for a swing also. At any instant of time the sum of the kinetic energy, the potential energy and the energy gained by air molecules must be the same. The total energy is conserved, though it can transform from one form to another and there are different methods of measuring the different forms of energy.

What is very striking is the fact that the laws of conservation get related to the symmetry of space and time in which we live. One can show that the law of conservation of energy



Sum of the potential energy and kinetic energy remains the same at any position

is directly related to the fact that the laws of nature are invariant under time translation.

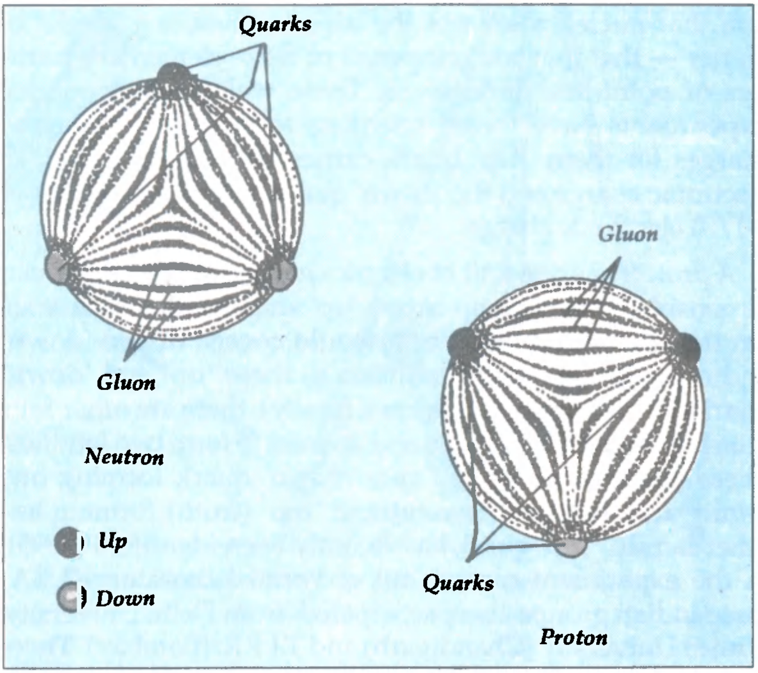
The law of conservation of linear momentum implies symmetry of space under translation. In other words, any experiment performed here will give the same result as performed at any other space point, provided all physical conditions remain the same. Law of conservation of angular momentum implies symmetry of space with regard to rotation. Besides these, there are other laws of conservation which determine the decay modes of elementary particles. We cannot go into all of these, but must mention the law of conservation of charge. It is this which accounts for the stability of the electron, as there are no charged particles lighter than it.

Experiments on the scattering of high energy electrons from nucleon led to some very strange results. Some electrons suffered large angle scattering, implying that the charge centres in the nucleons are highly localized. This led to a suggestion that nucleons are not the ultimate building blocks of matter — that they are composed of more elementary particles of point-like dimensions. These were named quarks. Experiments have forced scientists to postulate fractional charges for them. 'Up' quark carries an amount of (+2/3) electronic charge and the 'down' quark carries an amount of (–1/3) electronic charge.

A proton has one unit of electric charge and, therefore, can be considered as built up of two 'up' and one 'down' quarks. On the other hand, a neutron would consist of two 'down' and one 'up' quarks. In addition to these 'up' and 'down' quarks (which are said to form a family), there are other four quarks. These come in pairs and are said to form two families. These are 'strange' quark and 'charm' quark forming one family and 'bottom' (beauty) and 'top' (truth) forming another family. 'Top' quark has recently been identified (1995). In the experiment carried out at Fermi Laboratory (USA) three Indian groups also participated from Delhi University, Punjab University (Chandigarh) and T.I.F.R. (Bombay). There are conjectures that there may be yet another family of two quarks.

Quarks have spin $(1/2)\hbar$ and are, therefore, fermions. The other parameters which characterize quarks have been named *flavours* and *colours*. In a nucleon, quarks are bound together by a strong force. Its quantum is called a 'gluon'. The theory of interaction between quarks and gluons is called quantum chromodynamics (QCD).

The interaction between two quarks is represented by two different types of lines of force— one 'chromoelectric' and the other 'chromomagnetic'. Chromomagnetic lines of force represent interaction between gluons. As the quarks are pulled apart the chromoelectric lines get closer together and the chromomagnetic interaction increases. Eventually the chromoelectric lines become parallel and the whole thing appears like a string between the two quarks. This happens when the



Neutron and proton made up of quarks

quarks are about 10^{-15} metre apart. Because of the increased density of the chromomagnetic lines of force, the forces between the particles become very large and the quarks cannot pull apart. This is supposed to be the reason why quarks cannot be observed in the free state.

Thus, we have learnt as to how our concepts about atoms were formed and where we stand today. You might have observed that physics has made great strides in this century. It even upset such basic concepts as space and time, which man had taken for granted for centuries. In spite of all this, we can't yet say that we are close to understanding the atom. As we use higher and higher energy **projectiles (accelerators)** to investigate smaller and smaller distances, we keep on discovering newer objects, and there seems to be no way of saying whether this trend will stop at some level. Thus, it seems, for long time to come, the excitement in this field would continue.

Glossary

Acceleration: Rate of change of velocity.

Accelerator: Machine used to accelerate charged elementary particles in order to carry out collision experiments with nuclei.

Amplitude: Amplitude (in a periodic motion) is referred to as the maximum displacement in either direction, positive or negative, from its mean value.

Angular momentum: Essentially the product of moment of inertia and angular velocity of a body revolving about an axis.

Atomic number: Number of protons in a nucleus of an atom.

Atomic weight: The ratio of the average mass of one atom of naturally occurring element to (1/12) of the mass of an atom of carbon twelve.

Black body radiation: Radiation emitted by a hot body. It has a continuous energy spectrum.

Classical wave: Wave resulting from the wave-equation based on the concepts of classical physics; as for example, sound waves, water waves etc.

Density: Mass per unit volume.

Diffraction: Bending of a wave round the edges of an opening.

Elastic collision: A collision of two bodies in which kinetic energy before collision is the same as after collision.

Electromagnetic radiation: Radiation emitted by atoms or molecules when they return from an energetically higher excited state to a lower energy state. The radiation has both electric and magnetic components. Also radiation emitted by a black body.

Electrostatic force: Force between static charges of electricity. It is repulsive between identical charges (positive-positive or negative-negative), but is attractive between opposite charges (positive-negative).

Element: Material made of a single type of atoms.

Emission spectra: Spectrum of radiation emitted by a source. It may be a line, band or continuous spectrum. Plural of spectrum is spectra

Energy spectrum: Distribution of different constituents of radiation. Different constituents have different energy; as for example, break up of ordinary white light into different colours.

Fluorescence: Emission of light from a material during illumination by radiation of higher frequency.

Fusion (Nuclear): Coalescing of light nuclei in thermonuclear reaction to form a bigger nucleus.

Gluon: Elementary particle that mediates between quarks.

Intensity: A measure of rate of energy transfer by radiation. For classical waves intensity is proportional to the square of the amplitude.

Isotopes: Nuclei of an element which has same number of protons but different number of neutrons.

Kinetic energy: Energy possessed by a body by virtue of its motion.

Macroscopic scale: A scale which is much larger than atomic scale which are of the order of few angstroms (1 angstrom = 10^{-10} metre).

Mass: Quantity of matter in a body. Masses are compared by weighing and, therefore, referred to as 'Inertial' masses.

Mass number: Total number of protons and neutrons in a nucleus taken together.

Matrices: Plural of matrix. A matrix is a set of quantities arranged in rows and columns to form a rectangular array. It is used to represent relations between some quantities.

Momentum: Usually implies linear momentum. It is the product of the mass of a particle and its linear velocity.

Monochromatic radiation: Radiation of single precise energy. The energy is related with its wavelength which is often used to specify the colour of the visible radiation.

Nuclear force: Short-range force that keeps the neutrons and protons together in a nucleus. It is independent of charge.

Nucleus: The core of an atom; made up of protons and neutrons.

Photon: A quantum or packet of an electromagnetic radiation.

Potential energy: Energy possessed by a body by virtue of its position; the work done in changing the configuration of the body from some initial state to the final state.

Projectile: A body moving with a certain velocity.

Quantum: A packet of energy; for example, photon is a quantum of electromagnetic radiation. Quanta is plural of quantum.

Quantum mechanics: Branch of Physics which deals essentially with the description of elementary particles.

Quark: Particles which constitute neutron, proton and mesons (collectively referred to as hadrons).

Radioactivity: Spontaneous breaking up of atomic nuclei with the emission of *alpha* particles (helium nuclei), *beta* particles (essentially electrons) and *gamma* rays (energetic electromagnetic radiation) transforming the emitting nucleus into a nucleus of another element.

Scattering: When a moving body (particle) is allowed to interact with a system, its path is changed. Thin process is referred to as scattering.

Space point: Coordinates of a point in space.

Standard pressure: Pressure equal to 10^5 pascals (1bar); nearly 750 millimetres of mercury.

Standard temperature: Temperature equal to 298.15 kelvin or 25.15 degree celsius.

Static electricity: Electrical charges generated by friction. These charges are immobile and could be dangerous in some cases.

Superconductivity: Vanishing of electrical resistance in a material when its temperature is lowered below a critical temperature. Zero resistance implies infinite conductivity. Superconductivity is always accompanied by expulsion of magnetic field from the body of the superconductor.

Superfluidity: Phenomenon exhibited by liquid helium (^4He) below a critical temperature (~2 kelvin) where it flows without any resistance (viscosity).

Theological: Based on religious beliefs.

Wavelength: The least distance between two points in same phase in a periodic wave motion.

INQUISITIVE human mind has unravelled many a mystery of nature — from probing into the vast depths of the universe to peeping into the ultra-small world of atoms. The beginning of many of the modern concepts like atomic energy, radioisotopes, semiconductors, laser owe their origin to the concept of the atom, the minute constituent of matter. This concept in an age when science was still in its infancy was a conjecture of genius. Philosophers, Chemists, Physicists and Mathematicians, over long years, have contributed in the analysis and understanding of the intrinsic structure and nature of atom. The journey was a long and tortuous one. It is the tireless efforts of all those thinkers and experimenters that helped in revealing the microworld of the atom.

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