V. Rydnik

ABC's OF QUANTUM MECHANICS

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new concepts. It will describe how the new theory deciphered the secrets of the structure of atoms, molecules, crystals, atomic nuclei, and how quantum mechanics is dealing with the problem of the most fundamental of all properties of matter – the interaction of particles and the relationships between fields and matter.

Preface

At the turn of the century, physics entered into a new world, the invisible silent world of atoms, atomic nuclei and elementary particles. Our twentieth century then produced the theory that has been serving physicists so faithfully for over sixty years – quantum mechanics.

The landscape of the new world is quite unlike our own. So different that physicists frequently lack words to describe it. Quantum mechanics had to create new conceptions for the world of the ultrasmall, bizarre conceptions beyond the scope of pictorial imagery.

Customary physical laws cease to operate in the new world. Particles lose their dimensions and acquire the properties of waves. Then again, waves begin to act like particles. Electrons and the other building stones of matter can pass through impenetrable barriers, or they can vanish altogether leaving only photons in their place. Those are the things quantum mechanics dealt with.

This book will tell you about the origin and development of quantum mechanics, about its

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FROM QUANTUM MECHANICS TO...?

From classical mechanics to quantum mechanics

In Lieu of an Introduction

Atomic energy. Radioactive isotopes. Semiconductors. Elementary particles. Masers. Lasers. All quite familiar terms, yet the oldest is hardly twenty-five years of age. They are all children of twentieth-century physics.

In this age, knowledge is advancing at a fantastic rate, and every new step opens up fresh vistas. The old sciences are going through a second youth. Physics has pushed out ahead of all others and is pioneering into the unknown. As the front broadens, the attack slows up only to make renewed thrusts forward.

To get at the secrets of nature, physics has had to find powerful instruments, to devise precise and convincing experiments. At the physics headquarters are hundreds and thousands of theoreticians mapping out the offensive and studying the trophies captured in the experiments. This is no struggle in the dark. The field of battle is lighted up with powerful physical theories. The strongest searchlights of present-day physics are the theory of relativity and quantum mechanics.

Quantum mechanics came in with the twentieth century. Date of birth: December 17, 1900. It was on this day that the German physicist Max Planck reported to a meeting of the Berlin Academy of Sciences Physical Society on his attempt to overcome one of the difficulties of the theory of thermal radiation.

Difficulties are a common thing in science. Every day scientists come up against them. But Planck's encounter had a very special significance, for it foreshadowed the development of physics for many years to come.

An enormous tree of new knowledge has grown out of the seminal ideas expressed by Planck, which served as a starting point for amazing discoveries far beyond the imagination of the wildest science-fiction writers. Out of Planck's concepts grew quantum mechanics, which opened up an entirely new world – the world of the ultrasmall, of atoms, atomic nuclei and elementary particles.

The Outlines of the New World

But didn't people know anything about this atom before the twentieth century? In a way they did, that is, they had guessed and conjectured.

The inquisitive human mind had speculated upon these things and had long imagined what became a real thing only many centuries later.

In ancient times, long before the first travellers laid their paths of discovery, man had guessed that there were people and animals and land beyond the little area in which he lived.

In the same way, people felt that there existed a world of the ultrasmall long before it was actually discovered. One did not need to go far in search of this new world, for it was right at hand, lying around him in all things.

In olden times, thinkers had meditated on the way nature had produced the world around us out of something quite formless. How was it, they queried, that it came to be inhabited by its great diversity of things. Might it not be that nature worked like a builder that makes large houses out of small stones? Then what are these stones?

Enormous mountains are weathered away by the water, the wind, and mysterious volcanic forces. The rocks that come away are in time broken down into pieces. Hundreds and thousands of years pass, and these are pulverized into dust.

Is there no limit to this dividing and subdividing of matter? Are there particles so small that even nature is no longer able to break them up? The answer was YES. So said the ancient philosophers Epicurus, Democritus and others. These particles were given the name 'atom'. Their chief property was that no further division is possible. The word 'atom' in Greek means 'nondivisible'.

What did an atom look like? In those times, this question remained unanswerable. Atoms might be in the form of solid impenetrable spheres, yet they might not be. Then again: How many different varieties are there? Maybe a thousand, yet perhaps only one. Some philosophers (the Greek Empedocles, for one) believed that there were probably four. They believed that the entire universe consisted of four elements – water, air, earth, and fire. In turn, these elements were thought to consist of atoms.

One might now think that with information as meagre as this there could be no talk of any progress. True, yet the first steps of science are usually in breadth and not in depth. So many things surround man! The first job is to find out how they are related to one another, and then, only later, how they are constructed.

The conception of atoms in an age when science was still in its infancy was a conjecture of genius. But it was only a conjecture which did not follow from any kind of observations and was not supported by any kind of experiments.

The atoms were forgotten for a very long time.

They were recalled, or rather they were invented once again, only at the beginning of the nineteenth century. And not by physicists, but by chemists.

The start of last century was an interesting time both for the historian of society – Napoleon was recarving the boundaries of European states – and for the historian of science – in the quiet of the few laboratories that existed in those days there was in progress a radical reevaluation of the nature of things. Conceptions that had appeared quite stable were being reconsidered.

Young in England and Fresnel in France had laid the foundation of the wave theory of light. Abel in Norway and Galois in France had put the first stones in the mighty edifice of modern algebra. The Frenchman Lavoisier and the Englishman Dalton demonstrated that chemistry is capable of penetrating deep into the essence of things. The chemists, physicists and mathematicians of that time made a whole series of outstanding discoveries that prepared the way for the flourishing of the exact sciences in the latter half of the nineteenth century.

An unknown English scholar, Prout, in 1815 expressed the view that there exist minute particles which can participate in the most diverse chemical reactions without being destroyed and reconstructed. These were obviously atoms.

During those same years, the illustrious French scientist Lagrange put classical mechanics in that complete and elegant form in which – it was later found – there was no place for atoms.

The Temple of Classical Mechanics

In science, nothing appears from nowhere.

And quantum mechanics may justly be called the brain child of classical mechanics, which began with Newton.

True, it is not entirely right to attribute the creation of classical mechanics to Newton alone. Many great minds during the Renaissance were engaged in problems that later formed the basis of classical mechanics: Leonardo da Vinci, Galileo Galilei, the Dutch mathematician Simon Stevin and Frenchman Blaise Pascal. Out of all the scattered studies of the motions of bodies, Newton constructed a single unified and harmonious theory.

We know the exact date when classical mechanics was born. It was the year 1687, when Newton's book "Philosophia Naturalis Principia Mathematica" ("The Mathematical Principles of Natural Philosophy") appreared in London. In those days the natural sciences still went by the name philosophy.

In his work, Newton formulated for the first time the three basic principles of classical mechanics, later called Newton's three laws, which every schoolchild studies.

The edifice of mechanics that Newton built goes far beyond these three laws, and has long since been completed. From the vantage point of modern science, it looks like this.

In the enormous void of space inhabited by numerous and diverse objects, from gigantic stars to minute dust particles, there was a point in the distant past when the entire universe was without motion, in a state of complete rest.

It was god, who regarding in amazement the fruit of his creation, gave the first 'impulse' and breathed life into the world. This exhausted god's duties. From then on all the bodies in the universe began to move and interact according to definite laws. The number of such laws was great but in the final analysis they could all be reduced to several basic laws, which included the three laws of Newton.

From this minute on there was never anything accidental. Everything was predetermined. Nothing arbitrary was possible any more. From then on there was perfect harmony in this symphony of the universe.

For more than a century after Newton this supreme orderliness of the universe based on Newtonian mechanics was extremely satisfying to all physicists. They were pacified each time some new piece of the universe was found to fit nicely into the theory. And for quite some time nature allowed itself to be treated this way. But not for long. Scientists were soon convinced that there is nothing less stable than hardened dogmas. Facts began to appear that simply would not fit into the old framework.

By the end of the nineteenth century Newtonian mechanics was in a crisis. It gradually became clear that this crisis signified the fall of universal determinism, scientifically called the principle of mechanical determinism. The universe was not so simple after all, and it wasn't wound up for all time.

Quantum mechanics brought with it not only new knowledge. It gave a radically different interpretation to the phenomena of the world. For the first time, science gave full recognition to the accidental.

And perhaps physicists are not to blame for being taken aback. Though it was only the eternal determinism which they themselves had concocted that gave way, physicists seemed to think that it was determinism as such that was crumbling, that the universe was governed by absolute anarchy, and that things no longer obeyed exact laws.

It took quite some time before physics found its way out of the deep crisis.

The Temple Collapses

Curiosity killed the cat. The saying is probably applicable to theories as well. Even if today the theory appears quite correct and capable of explaining all the facts.

A theory puts in its appearance at a certain stage in the development of science, when the latter has made a study of a wide range of phenomena. The aim of the theory is to give an explanation from some one point of view.

But the very same theory proves insufficient and even erroneous when fresh facts are discovered that do not fit into its narrow framework.

Classical mechanics was entirely satisfactory as long as physics was confined to mechanics. But the nineteenth century saw physics attack a new broad front: thermal processes, which gave rise to thermodynamics; light, which gave rise to optics; electric and magnetic phenomena, which served as a starting point for electrodynamics. For a time, physics remained in a rather contented state. All new discoveries continued to fit neatly into the existing moulds.

However, as the edifice of classical physics grew upwards, its enormous front gave signs of fatigue, sinister cracks appeared, and finally the entire structure began to crumble under the bombardment of new facts.

One of these most fundamental facts was the remarkable constancy of the velocity of light. The most careful and objective experiments demonstrated that the behaviour of light is radically different from what had been observed in all other known areas.

To fit the behaviour of light into the framework of classical physics, scientists had to devise a medium called the ether, which, by the rules of classical physics, would possess simply fantastic properties. We shall come back to this ether later on and examine it in more detail. But the new ether could not save the old physics.

Another stumbling block to classical physics was the thermal radiation of heated bodies.

Then, finally, the discovery of radioactivity. This had the most shattering effect on classical physics during the last years of its undivided rule, for the mysterious processes of radioactivity not only smashed atomic nuclei, but exploded the very basis of physics – those principles that had appeared so obvious from the standpoint of common sense. Out of these cracks in the structure of classical mechanics grew the theory of relativity and the quantum theory.

How the New Theory was Named

Quantum mechanics was born at the turn of the century. But why this name? Actually, the term but feebly reflects the contents of the things which the new physics dealt with.

Probably not a single branch of physics has escaped a certain vagueness in terminology. There are many reasons for this, but they are primarily of a historical nature.

First of all, why mechanics? There was nothing mechanical in the new theory, and as we shall see later on, there couldn't be. The word 'mechanics' is justified only in that it is used in a general sense, like we speak of the 'mechanics of a watch' meaning the principle of operation. The conceptual range of quantum mechanics is better covered by the broad definition of physics itself.

Secondly, why quantum? Quantum in Latin means 'discrete portion' or 'quantity'. Further on we shall see that the new science does actually deal with 'discreteness' in the properties of the surrounding world. That is one of its basic principles. On the other hand, as we shall see, this discreteness is not at all general, and is not found everywhere or at all times.

What is more, it is only one side of the medal. A no less peculiar aspect is the duality of the properties of matter. The dual nature of matter lies in the fact that one and the same entity (object) combines the properties of particles and waves.

The new science was refined to 'wave mechanics'. But here again we have only half of it – there is no mention of quanta.

We conclude that none of the names of the new physical theory was satisfactory. But couldn't something be thought up more in keeping with the actual contents of the subject?

The introduction of new terms in science is a laborious and thankless job. New terms come in slowly and change still more slowly. Physicists understand the new meaning that these terms carry and so it is for us to learn them.

Physicists Build Models

Imagine the motion of a ball along a rope that you are whirling round your head. It is obviously quite simple because you can see everything with your own eyes. That is exactly how classical physics developed – out of the observations of objects and phenomena that surround us.

Roll a ball along a smooth horizontal table. It continues to move after the action of the hand has ceased, that is, after the force has ceased to operate. This and similar observations gave rise to the law of inertia that was enunciated by Newton as the first basic law of mechanics.

A ball will not begin to move until pushed by the hand or hit by another ball. A ball moving over a smooth table and a ball at rest have one thing in common: they are not acted upon by any forces.

On the rope, however, the ball is all the time acted upon by a force that deflects it from the rectilinear path inherent in free motion. That same ball at rest on the table will, under the action of the force of one's hand, begin to move and will acquire speed (the greater, the bigger the force). This observation gave rise to Newton's second law.

But now the investigator – Newton again – leaves the everyday world and looks to the heavens to seek a clue to the 'harmony of the celestial spheres' which had stumped the ancient philosophers. What makes the planets move round the sun in the way they do and not otherwise?

The word 'harmony' suggests a system of order, the operation of some law governing the motion of the heavenly bodies. The matter is not one of 'spheres' naturally. But there must be a law governing the motion of the planets, and our earth too, about the sun and the motion of the satellites about their planets.

One might recall the ball moving along a swinging rope. The motion of the planets about the sun is indeed very much like the uniform motion of the ball, though it is slower and there is no rope. In short, if in one case a force is operative, it is reasonable to suppose that it is operative in another case too.

There is of course no way to perceive directly the action of the force governing planetary motions. But the force is there. And Newton discovered it. We know that it is the force of the reciprocal attraction of bodies. Newton's genius lies in the fact that he perceived what is common between the motion of a ball and the orbital motion of a planet.

The important thing for us, however, is that the ball and rope was probably one of the first physical models. One gains an understanding of such a grandiose phenomenon of nature as planetary motion through the study of things on a much smaller scale – on the assumption of course that both are governed by similar laws.

The question arises as to whether this is justifiable everywhere and at all times. Is it right to extend the laws of one phenomenon to another one which is much larger or much smaller?

In Newton's time the answer was simple: since observation corroborates the development of some large-scale phenomenon that has been calculated on the basis of some small-scale one, or vice versa, everything holds true.

Roughly the same answer can be heard today as well. True, the approach is somewhat different. Newton believed firstly, that the universe was unified and, secondly, that the laws governing its life both at man's level and in the big world of the planets and stars are the same.

From the vantage point of modern science, we are in full agreement with the first.

Now for the second, we cannot of course draw the conclusion that the inner workings of a phenomenon follow from similar outer phenomena.

A parrot repeats human words, but it would be naive to suppose that while pronouncing a word the bird thinks.

The complexity of cognition lies in the fact that absolutely different laws are operative in the hierarchy of worlds of things – in the ultrasmall, the ordinary, the ultrabig; and that there are great limitations to extending the laws of the ordinary world of things to other scales.

Physicists have been frustrated, when encountering the unruly entities of the ultrasmall, due to a misunderstanding of this important conclusion. Once convinced that microscopic particles refuse to fit into the framework of ordinary concepts, these physicists began to speak of anarchy, of a nature without laws. Yet this was not the case at all, as we shall see later on.

Model representation has played, and continues to play, an important role in the development of the natural sciences. Some of the greatest discoveries have been made with the aid of models constructed by human hands or, more often, existing only in the mind, since they cannot be built.

The ball supported by a rope was a very simple model. As time went on, more sophisticated models were developed. They became more and more complicated, bizarre. But exotic as these models might become, they have one thing in common. They are built out of the elements of the ordinary world about us, the world we see and feel.

This is a peculiarity of the human mind. The most fantastic abstractions and generalizations always proceed from actuality.

Not Everything Can be Modelled

From the end of last century on, the familiar model approach to the investigation of new things in nature was not always a success. For instance, the ether model. Its creators saw it the saviour of classical physics, which was unable to account for the remarkable constancy of the velocity of light.

Let us try to picture this ether. Something absolutely solid and just as absolutely transparent. Unbreakable glass? And yet, despite its hardness, the ether had to allow for all kinds of bodies moving freely. What is more, these bodies should be able to entrain the ether, building up something like a wind, a truly ethereal wind.

For a number of years physicists attempted to grasp these fantastic properties of the ether. But they failed. The ether proved to be a construct with no roots in reality.

And the concept of ether was not the only rootless entity. Not a single model of classical physics for the atom was able to account for the mysterious release of energy by uranium, radium and other chemical elements – a radiation of energy that continues without interruption for many thousands and millions of years without any outside source.

Einstein's photon hypothesis was yet another blow to the old models. Through somewhat involved, it is still possible to fit into the classical model the concept of light as electromagnetic waves being propagated in all directions from their source.

We are accustomed to thinking of a wave as always being the motion of a material medium: the water for ocean waves, the air for sound waves. But electromagnetic waves are capable of propagation in an absolute void.

In this sense it is easier to picture light, as Newton did, as a stream of minute light particles. These particles are emitted by incandescent bodies, fly in all directions, and stimulate the optic nerve when they enter the eye, giving the sensation of light. There is now no difficulty in imagining how these particles move in empty space.

But to picture light having wave and corpuscular properties at the same time, as Einstein did, is something we simply can't do.

In the model of the atom constructed by Bohr and Rutherford we have a conceivable picture. Minute particles – electrons – are revolving in definite orbits around a tiny nucleus. The dimensions of the orbits are tens of thousands of times greater than those of the electrons and nuclei.

With a little more imagination we can picture the atom as a sort of 'empty' structure, for we ourselves live in a planetary system where the dimensions of the 'electrons' (or planets) are thousands of times smaller than those of the orbits about the 'nucleus' (or sun).

However, just a few years later de Broglie completely confused the picture by stating that the electrons, nuclei and generally all material 'building blocks' of our world have the same duality as that introduced by Einstein for photons; that is, they possess at the same time the properties of waves and corpuscles (particles). As a result, particles of matter, including atoms like those of light earlier, could no longer be visualized.

The Invisible, Untouchable World

Physicists were hard put. Before, they had trodden paths into new worlds, all the while sure that only the details would be different, not the essentials. But now they were in the shoes of explorers of old when anything could be expected, from monsters to half-beasts and half-humans. There is no limit to the imaginings of a feverish mind.

Physicists had it even worse than those explorers, for the latter were always pleasantly disappointed to find normal beings and essentially the same earth, mountains and seas, only arranged differently. In the new world, scientists saw such bizarre things that no name was suggestive enough. Even the imagination did not suffice to picture this unusual new world of the atom.

But developing science demanded that some kind of conceptions be worked out, no matter how unconventional they might be. It was hard to construct quantum mechanics but it had to be done.

It surely would have been easier to build theories based on visualizable models of the surrounding world. But what if the world of the ultrasmall was constructed differently? What if no such models could serve?

Well, if it is impossible to devise models that can be made into mental pictures, then we will have to work with models that cannot be pictured at all. Years passed, not many though, and these models became so 'unvisualizable', yet so dear to physicists that no one wants to give them up. Which is too bad, because the time will come very soon – if we run ahead in our story a bit – when all these models will have to be jettisoned and replaced by still more unusual ones that will be even harder to grasp. That is how science develops.

Therein lies the greatness of the physicists of this century: they were able to reach their goal through a maze of abstractions and models far removed from everyday things, they succeeded in constructing a far-reaching theory of the new world of the ultrasmall. What is more, on this basis, physicists achieved some of the greatest things in the entire history of civilization. They discovered the secret of nuclear energy, the jinni that had been bottled up for so long.

The atomic power industry and electronics would not be here today without the existence of quantum mechanics.

Difficult but Interesting

The unusual nature of quantum mechanical notions and the fact that these concepts cannot be visualized properly make the subject difficult to grasp. True, some of the fault lies in quantum mechanics itself. Not only because its range is continually expanding and its methods are constantly undergoing refinement; we know that it is always more difficult to write about something in a state of flux and development, and particularly such rapid development, than it is about firmly established theories. Not only this, but also because physicists themselves are still, to this day, arguing about the very meaning of quantum mechanics, about the specific aspects of the minute world that it describes.

We have now entered the space age, where again physics is called upon to pave the way. The physics of cosmic space differs radically from 'terrestrial' physics in that the world of the ultrasmall is of prime importance.

The ancient idea of the great and the small meeting finds its confirmation in outer space. Enormous stars and minute atoms not only converge but exist as an integral unit.

It is almost impossible to write popularly about science without resorting to some kind of visual representations. And so with quantum mechanics we shall try to find analogies, if not models, in nature. However, such analogies are in no way exact or profound. They simply help us to get a general grasp of things.

For instance, as we shall see, the phrase 'electrons revolve around an atomic nucleus' hardly has more meaning to us than the words 'snow is something white, rather like salt and falls from the sky' have for the inhabitants of tropical Africa. The motion of an electron in an atom and the essence of the electron as such is immeasurably more complicated than what we know about them today and the way we picture them. And not only today, tomorrow and a thousand years hence!

Indeed, the development of quantum mechanics is added proof of the limitless diversity, the inexhaustibility of the properties of the electron. And everything else as well.

We today still have rather fragmentary knowledge of the world about us. We are only beginning to penetrate into the earth's crust, into the oceans, the atmosphere. We have only just started to understand the life of the fields, the forests, the mountains, the rivers and the deserts.

If that is so, how can we expect to know as much about the world of atoms, atomic nuclei and elementary particles, which are still more difficult to observe.

There is exploration ahead in this science for hundreds and thousands of years. As yet we are only at the source of a mighty river of knowledge.

Even so, what amazing things are revealed to the explorer of this recently discovered world. What inspiring, truly fantastic horizons does this new science open up for technology, industry, agriculture and medicine. Nuclear power stations, radioactive isotopes, solar batteries, to name a few. We are on the threshold of controlled thermonuclear reactions and we are penetrating into outer space. All these great attainments of the bright present and the dazzling future were born in our century out of a small seed thrown, sixty years ago, into the fertile soil of scientific knowledge by Max Planck and, since, carefully cultivated by a whole galaxy of brilliant scientists.

The first steps of the new theory

Heat and Light

It's nice, on a cold winter evening, to sit near a hot stove and listen to the sputtering flames inside and feel the warmth of the fire. But why warmth? Why is it warm near a stove? Without even seeing the fire inside, one can feel the heat at some distance away.

A stove emits some kind of invisible rays that give the sensation of heat. These rays are called heat rays, or infrared rays.

A little careful observing will show us that thermal radiation is quite a common thing in nature. Both heat and light are emitted by a candle, a large fire, and our enormous sun. Even the fantastically distant stars send heat rays to the earth.

If a heated body glows, it definitely is emitting heat rays as well. The emission of light and heat is actually one process. That is why scientists gave the name thermal radiation to all emissions of a body that appear to be due to a heating process – both the emission of light and the thermal radiation proper.

Last century, physicists had already discovered the basic laws of thermal radiation. They are familiar to all of us. Let us recall two laws.

First, the more a body is heated, the brighter it glows. The quantity of radiation emitted per second varies drastically with change of temperature of the body. If the temperature is increased three times, the radiation will increase almost one hundredfold.

Second, the colour of the emission changes with an increase in temperature. Observe a piece of iron pipe under the flame of a torch. At first it is quite dark, but then a faint crimson tinge appears, this turns red, then orange and yellow. And finally the heated metal begins to emit a white light.

An experienced steelworker can gauge the temperature of an incandescent pipe quite accurately by the colour of luminescence. He will say that a faint crimson tinge means a temperature of about 500°C, yellow is about 800°C, and bright white is over 1,000°C.

Physicists are not satisfied with this rough qualitative description, they want exact figures. To a physicist, 'the day is cold' means about as much as 'he had a big face'. What one needs is the peculiar features, the nose, the lips, the forehead.

Physicists had encountered a great diversity of bodies and conditions in which thermal radiation is emitted. But this diversity of conditions did not satisfy them in the least. They wanted some kind of 'standard' body, a criterion to be used as a basis for establishing the laws of radiation of heated bodies. Then the emission of light by other bodies could be regarded as deviations from the 'standard'. Picture a description like this: "The nose of the man was longer than the standard nose, the forehead was narrower, the jaw more extended, the eyes somewhat greener and somewhat smaller than normal." Rather strange to us, but the physicist would be delighted. Here's why.

Blacker than Black

Take a number of objects of the same colour, as close as possible. Now examine them and try to see how they differ in colour.

A careful examination will show that there are differences. One has a faint tinge, another has a deep, rich colour. The difference is due to the fact that a certain amount of light falling on the body is absorbed and a certain amount is reflected. Naturally, the relationships of these two amounts can vary over a tremendous range. To take two extreme cases, a shiny metallic surface and a piece of black velvet. The metal reflects almost all the light that falls on it, while the velvet absorbs most of the light and hardly reflects any.

Magicians make good use of this property of velvet, for if an object does not reflect much light, it is practically invisible. On the stage, a box covered with black velvet on a black background goes quite unnoticed, and the magician can go through all kinds of tricks with handkerchiefs, pigeons and even himself appearing and disappearing.

Physicists also found this property of black bodies very valuable. In the search for a standard body, they decided on the black body. A black body absorbs the most radiation and, hence, is heated by this radiation to a higher temperature than all other bodies.

Conversely, when a black body is heated to a high temperature and becomes a source of light, it radiates more intensely at the given temperature than any other bodies. This, then, is a very convenient radiator for establishing the quantitative laws of thermal radiation.

However, it was found that black bodies themselves emit radiation in different ways. For example, soot may be blacker or lighter than black velvet, depending on the fuel it comes from. And velvet too can differ. These differences are not great, but it would be good to get rid of them.

Then physicists thought up the 'blackest' body of all, a box. A very special kind of box to hold thermal radiation. It was ribbed with inner walls covered with soot. A ray of light enters through a tiny aperture and never gets out again, caught for all time. The physicist says that this box absorbs all the radiant energy that enters it.

And now let us make the box a source of light; actually, this is what it was intended for. When heated sufficiently, the walls become incandescent and begin to emit visible light. As we have already said, for a given temperature the thermal and light radiation of such a box will be greater than for any other bodies, which are then called grey to distinguish them from our box.

All the laws of thermal radiation were established precisely for the 'very blackest' boxes, which were given the generic name 'black bodies'. With slight alterations, these laws apply also to the grey bodies.

Exact Laws, Not Rough Approximations

Let us now redefine our laws more exactly, in the language of physics.

The first states that the radiating capacity of a black body, that is the energy it emits in the form of light and heat every second, is proportional to the fourth power of its absolute temperature.* This law was

* Absolute temperature is reckoned from 273 degrees below 0 degrees Celsius.

discovered at the end of last century by the German scientists Stefan and Boltzmann.

The second law states that as the temperature of a black body increases, the wavelength corresponding to maximum brightness of the light emitted by it must become shorter, and is shifted towards the violet region of the spectrum. This was called Wien's displacement law in honour of the Austrian physicist W. Wien.

Physicists now had at their disposal two universal laws of thermal radiation that could be applied to all bodies without exception. The first gives a correct description of increasing brightness of luminescence as a body is heated. It might appear that Wien's law is in poor agreement with observations, since as the temperature increases, the body emits more and more white light. White, not violet.

But let us take a closer look. The Wien law only speaks of colour corresponding to maximum brightness of light radiation, and nothing else. It is tacitly assumed that in addition to this radiation there remain the radiations of longer wavelengths (i. e., of a different colour) that had started earlier at a lower temperature. When a body is heated, its radiation widens the spectral range, opening up fresh regions of the spectrum. As a result, if the temperature gets high enough, we have a complete visible emission spectrum.

This might be compared to an orchestra in which more and more instruments come in with higher and higher notes until the whole ensemble sounds in one mighty accord, from the deep 'red' base of the trombones to the highest shrill 'violet' of the piccolos. And white light is the whole spectrum at once. Wien's law holds true. But nature dealt a blow to the investigators of thermal radiation from quite a different angle.

The Ultraviolet Catastrophe

Physicists have a penchant for universal laws. As soon as it is discovered that one and the same phenomenon is described, in various aspects, by several laws, an attempt is immediately made to combine them into a single general law encompassing all aspects at once.

Such an attempt was made, with respect to the laws of thermal radiation, by the English physicists Rayleigh and Jeans. The unified law which they obtained stated that the intensity of radiation emitted by a hot body is directly proportional to the absolute temperature and inversely proportional to the square of the wavelength of the emitted light.

This law appeared to be in good agreement with experimental findings. But it was suddenly discovered that the agreement was good only for the long-wave portion of the visible spectrum, the green, yellow and red. The law broke down as the blue, violet and ultraviolet rays were approached.

From the Rayleigh-Jeans law it followed that the shorter the wavelength, the greater should be the intensity of thermal radiation. Experiment failed to confirm this. What is more, a very unpleasant thing was that as we move to shorter and shorter wavelengths the radiation intensity was supposed to increase without bound!

Of course, this doesn't occur. There can never be an unbounded growth in wave intensity. If a physical law leads to 'unboundedness', it is doomed. Nature has large things, very large, even unimaginably large things, but there is nothing without bounds, except the universe itself.

This curious situation that arose in the theory of radiation became known as the 'ultraviolet catastrophe'. That was at the end of last century. At that time, nobody could even imagine that it was not simply a catastrophe for one, rather special, law. It was the collapse of the entire theory that gave birth to the law – the catastrophe of classical physics!

Classical Physics at an Impasse

There were physicists in those days who did not regard this radiation-theory obstacle in the path of classical physics as significant. But any hindrance is a grave matter, for everything in the theory is interrelated. If some point is false, we cannot rely on the description it gives of other phenomena. If the theory is not able to overcome a little barrier, what hope is there for big barriers?

Physicists made heroic attempts to surmount the difficulties of radiation theory. Today, these attempts seem logically inconsistent. Yet what can one expect? When a theory gets into a hot spot, it is like a cat in a burning house with one way out – into the river. The cat races from corner to corner, but it never thinks to jump into the water, for that would be against all the cat's instincts.

Something similar happens to scientists who are caught 'burning' in the house they have worked all their lives. The house which is so dear to them and to which they are so accustomed. They try to put the fire out, but they can't conceive of running away and leaving it.

However, it became clear to the more acute scientists that classical physics had reached an impasse. And the theory of thermal radiation was not the only blind alley. Those same years saw the ether theory collapse too.

The breakdown was so rapid that many were in complete despair. What was there left to do?

If the facts don't fit the theory, so much the worse for the facts. Nature does not want to obey any laws. "Nature is unknowable!" said some thinkers.

The reaction of the materialist-thinking scientists was different. If the facts cannot be explained by the theory, so much the worse for the theory. It will have to be reconstructed on a new basis, and immediately.

History once again demonstrated that great necessity gives birth to great men. The way out of this cul-de-sac of classical physics with its immutable dogmas was found by Max Planck, who in 1900 introduced the concept of quanta, and by Albert Einstein, who in 1905 advanced the theory of relativity.

The Way out

What was Planck's discovery?

At first glance it is hard to call it a discovery.

There were two laws dealing with the thermal radiation of hot bodies. Separately, they held true very well, but when joined into a single law it confronted the 'ultraviolet catastrophe'. Something like two men meeting with just about the same way of thinking; after a little discussion they come up with absolutely 'mad' ideas.

Planck at that time was over forty. For many years he had been studying thermal radiation. Right before his eyes the theory had come to an impasse; like his colleagues, he was seeking a way out. He checked the entire chain of reasoning and was finally convinced that there was no mistake. Planck then went further and in a different direction.

In later years he recalled how he had never worked so hard and with so much youthful energy and inspiration as in those years at the turn of the century. The most improbable things began to appear to him quite possible, and with the persistence of the fanatic, Planck went through one version of the theory after another.

At first he was guided by a rather simple idea. Rayleigh and Jeans had combined the two laws of thermal radiation into one and had obtained an absurd result for short wavelengths. Maybe it is possible to link up the laws of Wien and Rayleigh-Jeans in a different way and get something reasonable.

For his experimental material, Planck tried to find some general formula that did not contradict the material. After some search he found such a formula. It was rather involved. It contained expressions that do not have obvious physical meaning – just an accidental combination of unrelated quantities. But strangely enough, this concocted formula was in excellent argeement with experiment.

What is more, from it Planck was able to derive the Stefan-Boltzmann law and the Wien law. And taken as a whole, the formula did not have any 'infinities'. A correct formula, the physicist would say.

Victory? A way out? Not exactly. Planck, a real scientist, was inclined to doubt.

Hitting the keys of a piano twenty times at random might yield a tune, but where is the proof that it must produce a melody? The formula had to be deduced from something. Science does not recognize the rule whereby the winner is not criticized. On the contrary, he always is, and very fundamentally. Until the winner can prove every step in his competition with nature, victory is not recorded.

And it is here that Planck failed. The formula did not want to be derived from the laws of classical physics. Yet, it fit the experimental data in miraculous fashion.

That was the dramatic situation in which Planck found himself. Would he take the view of classical theory against the facts or would he stand by the facts and fight the old theory? Planck took the side of the facts.

Quanta of Energy

What was it in classical physics that made it impossible to derive Planck's formula? Nothing less than one of its most fundamental premises: the statement, so common and unshakable to the physicists of those days, that energy is continuous.

At first glance this would seem to contradict the spirit of classical physics, which from the very start recognized the discontinuity of things as an underlying principle. It appeared quite obvious. If we have empty space in the world, all objects have to be separated from one another and have boundaries. Objects do not pass one into another in continuous fashion, each one ends at some point.

Maybe the situation is different inside things. No, there doesn't seem to be any continuity here either. Classical physics, at the end of the 19th century, was forced to recognize the existence of molecules and of empty space between them. The molecules had clear-cut boundaries, and only the void between was continuous.

Incidentally, molecules somehow managed to interact through this emptiness. Since the time of Faraday, classical physics had been trying to account for such interaction by the existence of some sort of intermediate medium, via which the mutual action effects of the molecules were conveyed.

What about energy, though? It was held that when molecules collided, energy was exchanged in every imaginable quantity. This exchange followed exactly the laws of billiard balls. A moving molecule hits a stationary one, gives up part of its kinetic energy, and the two molecules then wove off in different direction. In a head-on collision, the incident molecule can even come to a stop; then the struck molecule will fly off with the speed of the first one (if their masses are equal). Molecules are constantly exchanging energy.

Another form of energy was found, one not obviously connected with molecular motion – the energy of wave motion. Since Maxwell proved that light is electromagnetic waves, the energy of light radiation (of thermal origin, for instance) must follow the laws obeyed by all waves.

Again, this energy is continuous. It is propagated together with the moving wave, flowing like water. Any given quantity of energy is consumed continuously in the same way that water continuously and indivisibly fills a vessel.

When we cut off a piece of butter, we do not think about the continuity of the piece. We assume that it can be made as small as we please. When the concept of molecules was introduced into science, it became clear that there was no such thing as a piece of butter smaller than a molecule of butter.

Now with regard to energy, there was no such notion of discreteness. It appeared that the atomic structure of matter did not demand that energy be composed of 'pieces'.

It was enough to look around us to see that that was so. The light from a candle filled a room with an even flow of radiant energy, just as the sun kept up an uninterrupted stream of light. Or take the smooth build-up of speed (and with it, energy) of a locomotive moving downhill, of a falling stone.

Imagine for a moment that energy is acquired and given up in little portions. One calls to mind the jerky movies of years ago. One pictures the candle flaring up and dying down, the sun shining in bursts, as it were, a flash of radiant energy, and then a lull until the next flash. The train moving down a slope in jerks, the stone bumping along through the air in its plunge to earth.

"Sheer nonsense!" was the answer Planck most likely got from his first suggestion that the energy of radiation (like matter itself) is atomistic and that it is released and acquired not continuously but in small portions, quanta, as Planck called them, from the Latin 'quantum' meaning quantity. If he had only known the quality that would eventually grow out of such quantity!

For Planck's formula, quanta were vitally important. Without them, it would have failed miserably and would have gone to the dusty archives of science along with so many others that have found no substantiation.

These quanta of energy served as a firm foundation for Planck's formula. But the foundation itself rested on practically nothing since there was no place for it in classical physics. That is exactly what troubled the cautious Planck. It is no easy matter to give up a lifetime of habit.

The Elusive Quanta

A quantum of light is an extremely small portion of energy. The most minute particle of dust has thousands of millions of atoms. The radiant energy released by a tiny glow-worm contains thousands of millions of quanta.

Now we come to the magnitude of these separate portions of energy. Planck made the extremely important discovery that such portions differ for different types of radiation. The shorter the wavelength of light, that is the higher its frequency (in other words, the 'more violet' it is), the larger the portion of energy.

Mathematically, this is expressed by means of the well-known Planck relation between the frequency and the energy of a quantum:

$$E = h\nu$$

Here, E is the energy carried by the quantum; ν is the frequency of the quantum; h is a proportionality factor which turned out to be the same for all types of energy that we know. It is known as 'Planck's constant' or the 'quantum of action'. The value of this number is just as great to physics as its magnitude is small: 6×10^{-27} erg per second!

It is this insignificant magnitude of the quantum that makes the light of a candle or the sun appear to us to burn with a constant glow. To illustrate, let us calculate the number of quanta radiated by a 25-watt electric light bulb per second. Taking the emitted light to be yellow, we find by Planck's relationship 6×10^{19}, which is 60 million million million portions of energy per second. All of that is radiated by a small 25-watt bulb every second!

Quite obviously, the human eye is not sensitive to such magnitudes of energy. Yet this is not so. The eye is an extremely sensitive instrument, as was convincingly demonstrated by the experiments of the Soviet physicist S. Vavilov. An observer was kept in the dark for a certain time (to increase the sensitivity of the eye) and then an exceptionally weak source of light that yielded just a few quanta per second was switched on. The eye recorded them almost as separate entities!

The point is not the magnitude of the quanta but the very high rate at which they follow one another. We have already seen that even a small lamp emits millions upon millions of millions every second. Now the human eye, like any other instrument, operates with a time lag. It is not able to record events that proceed in rapid succession. This inertia-like property of the eye is what makes moving pictures possible. We see the screen as a continuous sequence of events, although we know that the pictures are actually in the form of separate frames. Energy quanta emitted by sources of light follow one another much more rapidly, and so the human eye sees light as one continuous flow.

Vavilov conducted his experiments in the 1930s, when Planck's notion of quanta was generally recognized. Planck himself was not able to prove his discovery by direct experiment.

The fact that a formula is corroborated by experiment but does not follow from theory always appears at first somewhat dubious. In this case, all the more so since the formula was obtained from reasoning that ran very much against the grain of accepted thought. That was why there was not much enthusiasm in scientific circles when Planck delivered his communication at the Berlin Academy of Sciences. Scientists are human beings, too, and they require time to digest something so out of the ordinary.

Planck himself was fully aware of the boldness of his attack on classical physics and was eager to justify it. But of course he could never imagine the tremendous developments that revolutionized the whole of physics just a few years later.

The first years of the twentieth century, 1901, 1902, 1903, 1904, went by with hardly any attention paid to the theory of quanta. The number of scientific papers that appeared could be counted on one's fingers.

An Unaccountable Phenomenon

But then in 1905, a totally unkown member of the Swiss Patent Office, Albert Einstein, published his theory of the photoelectric effect in metals in the German journal "Physikalische Rundschau".

At the time that Einstein took up this study, the effect was well on in years. It had been discovered in 1872 by A. Stoletov, professor of Moscow University. Later on it was studied by the German physicists Hertz and Lenard.

Stoletov had pumped the air out of a flask, put two metallic plates inside and attached them to the poles of an electric battery. Naturally, there was no current through the airless space. But when the light of a mercury lamp was made to fall on one of the plates, current immediately began to flow in the electric curcuit. When the light was turned off, the current stopped.

Stoletov drew the proper conclusion, that current carriers (later found to be electrons) had appeared in the flask and that they originated only when the plate was illuminated.

It was quite obvious that these electrons were ejected from the illuminated metal much like molecules jump into the air from the surface of heated liquid. However, the words 'much like' really mean 'quite differently from'; the ejection of electrons from metal was fundamentally different and, what is more, was of an unknown nature.

To begin with, light is an electromagnetic wave. It is difficult to imagine how a wave can knock electrons out of metal. There is no collision here of energetic molecules, as a result of which one of them is ejected from the surface of a liquid.

Another interesting circumstance was noted. For each metal studied, there appeared to be a certain limiting wavelength of incident light. When the wavelength was exceeded, the electrons in the flask disappeared at once and the current ceased to flow no matter how strong the light was.

This was altogether strange. It was clear that electrons are ejected from the metal because the light in some way conveys energy to them. The brighter the illumination, the stronger the current. The metal receives more energy and larger quantities of electrons can be knocked out.

But no matter what the wavelength of the light, the metal should be receiving energy all the same. True, with increasing wavelength the energy diminishes and fewer electrons are ejected from the metal, but still there should be some kind of current. Yet experiment showed no current at all. One would think the electrons ceased to accept the radiant energy.

Why were electrons so particular about the energy food they were given? That was something that physicists just could not grasp.

Photons

Einstein regarded the photoelectric effect from a different angle. He attempted to picture the actual process of the ejection of an electron from a metal by light.

In normal conditions, there is no cloud of electrons hovering over the metal. Which would suggest that the electrons are bound to the metal by some kind of force. To knock them out of the metal, a little energy is needed. In Stoletov's experiments this energy was supplied by light waves.

But a light wave has a definite wavelength, something of the order of a fraction of a micron, and its energy is, as it were, concentrated in the minute volume occupied by an electron. This means that in the photoeffect a light wave behaves like a tiny 'particle'. It strikes an electron and dislodges it from the metal.

This must obviously be a particle of light; as Newton would say, a corpuscle, because Newton regarded light not as waves but as streams of particles. Then what would the energy be of such a particle? Calculations show that it would be very small. Then why not suppose that it would be exactly equal to the quantum that Planck had conjured up five years before?

So Einstein said that light is simply a stream of quanta of energy, all the quanta of a single wavelength being exactly the same, which is to say that the quanta carry identical portions of energy. Later, these quanta of light energy were given the name photon.

The explanation now was complete. A photon carrying a small portion of energy strikes an electron with sufficient force to knock it out of the metal.

On the other hand, obviously, if the photon energy is insufficient to disrupt the electron bonds in the metal, the electrons will not be knocked out and there will be no current. According to Planck's formula, the energy of a quantum is determined by its frequency, and the greater the wavelength of the light, the lower the frequency. Hence it is quite obvious that the photoelectric effect has definite limits. It is simply this: if the wavelength of the light is too large, the photons do not have energy enough to dislodge electrons from the metal.

What is more, it doesn't make any difference how strong the light is, whether a thousand or only two photons strike the metal and bombard its electrons: the latter are indifferent. The situation changes if the photons have sufficient energy. In this case, the brighter the light, the more photons enter the metal every second, and the greater the number of electrons ejected, thus producing a stronger current.

Thus, an explanation has been found. But, like the Planck hypothesis, it undermines the foundations of classical physics, where light is considered to be electromagnetic waves and under no circumstances these new-fangled photons. Einstein's theory again started up the two-century argument over the essence of light.

What is Light?

Actually, there was never any let up in the argument. The problem arose at the dawn of classical physics and lived a tempestuous life. The dilemma was: what is light, waves or particles?

Both viewpoints appeared in physics at about the same time. Bodies shine by ejecting streams of light particles, corpuscles, said Newton. Bodies shine by pulsating and forming waves in the surrounding ether, said Newton's contemporary, Huygens, of Holland.

Each theory had its adherents, and they clashed from the start. It was a fierce struggle that went on for over a hundred years, first one side winning and then the other.

Finally, at the beginning of the nineteenth century the experiments of Young, Frensel and Fraunhofer resulted in what would have seemed a decisive victory for the wave theory of light. The newly discovered phenomena of interference, diffraction and polarization of light were in excellent accord with Huygens' theory and quite incomprehensible from Newton's viewpoint.

Optics began to develop. Brilliant optical theories were developed and complex optical instruments were constructed. Finally, Maxwell completed the structure of optics by proving the electromagnetic nature of light waves. The triumph of the wave theory was complete and indisputable.

But less than fifty years passed and the corpuscular theory of light was again revived. The photoelectric effect which the wave theory had failed to explain – what an annoying blemish on an otherwise perfect structure! – was accounted for in amazing fashion by the opposing theory.

The century-old argument again flared up. But now the fight was on a new level. Both adversaries were tired out and ready for a compromise of some kind. Gradually it dawned on physicists that the amazing and inevitable view had to be that light is at the same time both waves and particles!

But why is it that light never manifests itself completely in this twofold manner? Sometimes it appears only as particles, yet at other times it is only in the form of waves. We shall take that important question up later on.

The second question that came with Einstein's theory was not simple either. It appeared that in the photoelectic effect the electrons did not react to just any portion of energy offered them. The portion of energy had to be of a very definite magnitude or greater, otherwise the light energy found no response.

It also turned out that an electron which is not bound by any forces to neighbouring ones ceases to be particular and responds to all kinds of energy packets. But if the electron should find itself in a metal, it gets moody and demands specific portions of energy again.

Why this is was explained some twenty years later.

The Visiting Cards of Atoms

Meanwhile, a young Danish physicist, Niels Bohr, tried to apply the new quantum concepts to the respectable science of spectroscopy. By the twentieth century, hundreds of papers had appeared dealing with spectroscopy. Spectral analysis was moving ahead at quite a pace doing great service in chemistry, astronomy, metallurgy and other sciences.

Credit for the discovery of spectra goes to the diversified genius of Newton. But spectral analysis made its appearance only a century ago. In 1859, the prominent German chemist Bunsen repeated Newton's old experiment by placing a glass prism in the pathway of the sun's rays and decomposing the light into a spectrum. In Bunsen's experiment, the role of the sun was played by a burning rag dipped in a salt solution. Newton had found that a ray of sunlight is expanded into a band of many colours. Bunsen didn't see any band at all. When the rag had table salt (sodium chloride) on it, the spectrum exhibited only a few narrow lines, nothing else. One of the lines was a bright yellow.

Bunsen got another well-known German scientist, Kirchhoff, interested in this fact. Both of them correctly concluded that the role of the glass prism consisted only in sorting the incident rays of light into their wavelengths. The extended band of the solar spectrum indicated that all the wavelengths of visible light were present. The yellow line, which appeared when the light source was a burning rag, indicated that the spectrum of table salt had a single specific wavelength.

The formula of sodium chloride is NaCl. To which element (sodium or chlorine) did the yellow line belong? This could be checked very simply. The sodium could be replaced by hydrogen, giving us hydrogen chloride, HCl, which, when dissolved in water, yields hydrochloric acid. The rag was dipped in hydrochloric acid and placed in the flame of a Bunsen burner and the spectrum was taken. The yellow line had disappeared without a trace, which meant that it belonged to sodium.

This was verified once again. The sodium was retained, and the chlorine was replaced (caustic soda, NaOH). The familiar line appeared in the spectrum immediately. There was no longer any doubt. No matter what the substance in which sodium appeared, it made its whereabouts known by the bright yellow spectral line, its visiting card.

Later, it was found that sodium is no exception in this respect. Every chemical element has its own characteristic spectrum. As a rule, some of the spectra were much more complicated than that of sodium and consisted at times of a very large number of lines. But no matter what the compound or substance the element appeared in, its spectrum was always distinct, like the photograph of a person.

One might look for a person in a crowd by checking the identification card of each one, like chemists do when looking for elements in rock specimens using chemical methods of analysis. But an easier way is to have his photograph. Which is precisely how the search is done with the aid of spectral analysis. And the elements are found in places where 'looking over identification cards' would be out of the question – on the sun, in distant stars, in the inferno of blast furnaces and in plasma.

All that it needed is the photographs of all the participants. Today there are over a hundred chemical elements, and nearly all of them have been classified according to their characteristic spectra.

Why do Bodies Emit Light?

The successes of spectral analysis were colossal, but there was a fundamental flaw. The edifice of spectroscopy was erected on the foundation of the theory of thermal radiation and bore all the traces of the basic shortcoming of this theory. The basic weakness lay in its answer to the question: Why do bodies begin to emit light when heated?

How is this light emitted? Obviously, by the component parts of the bodies – atoms and molecules. Increasing temperatures make the molecules move faster. Mutual collisions are more violent and more frequent, and the molecules vibrate so fast that they begin to emit light. That was the view of the old physics. But then why do not bodies luminesce at room temperature, since the molecules are still in motion? No explanation was then forthcoming.

When, in 1898, the English scientist Thomson created the first model of the atom, the mystery of luminescence seemed about to be solved. In this model, atoms were clouds of positive charge within which floated negative electrons in quantities sufficient to balance the charge. The electrons were attracted by the positive clouds and retarded in their motion.

But according to classical physics, charged particles have to emit electromagnetic radiation when they are decelerated. Apparently, that radiation is the light emitted when bodies are heated. At first glance, the explanation was quite convincing. The more a body is heated, the faster the electrons move in the atoms and the greater the deceleration due to the attraction of the clouds of positive charge, and hence the more intense the radiation.

That could be the case if electrons did not expend energy when radiating. But when electrons radiate light, they must decelerate with extreme rapidity. In just the most minute fraction of a second they would have bogged down in the positive clouds like raisins in pudding.

Something was wrong. Several years later it became evident that the Thomson model of the atom would not work in other respects as well. Too many questions remained unanswered. And then why don't the electrons simply merge with the positive cloud and neutralize their charge? The few answers that are obtainable from this model come into sharp conflict with experiment in most cases.

In 1911, the eminent English physicist Ernest Rutherford proposed a new model of the atom. Rutherford bombarded atoms of various substances with the newly discovered alpha rays of radioactive material. It was already known that these rays consist of positively charged particles.

Studying the scattering of alpha particles by atoms, Rutherford was forced to a conclusion with far-reaching consequences. The alpha particles were scattered as if they were repulsed not by the entire positive cloud of the Thomson atom, but by a very small portion of the atom concentrated somewhere at the centre. The entire positive charge of the atom appeared to be concentrated in this tiny central part.

Rutherford called this part of the atom the core (nucleus). Then where are the electrons? The old view that the electrons were bound to the positive charge in the atom by the electric forces of attraction was not in doubt. But since the electrons exist at a certain distance from the core, there must be some force that counterbalances the electric force of mutual attraction of electrons and nucleus.

It was obvious that this force had to be operative all the time. Atoms exist for a sufficiently long time, and so the countering force would obviously have to be just as constant as the force of electrical attraction between electrons and nucleus.

It seemed reasonable to think that this was a centrifugal force. It appears if electrons revolve about an atomic core. It could be calculated whether the force is sufficient to keep the electrons from falling into the nucleus. Calculations showed that it is quite sufficient if the electrons revolving about the nucleus move at speeds of many tens of thousands of kilometres per second and at a distance from the nucleus of the order of hundred millionths of a centimetre.

This was the Rutherford model of the atom. A ball swinging round at the end of a rope had indirectly suggested to Newton the idea of planetary gravitation; this same idea now led Rutherford to the ingenious and perfectly correct (as the future has shown) concept of a planetary structure of the atom.

Now we can return to the problem of why bodies emit light and seek the answer in the new model of the atom. The motion of electrons about the nucleus is accelerated motion (the electrons move along closed curves). Hence, there must be electromagnetic radiation. The classical laws are equally applicable to the Thomson model and the Rutherford model of the atom. But, unfortunately, the success is also the same. In radiating light, an electron uses up its energy. In doing so, it slows down in millionths of a second and must inevitably fall onto the nucleus, just like a satellite decelerated in the earth's atmosphere falls to earth. The fate of the electron should be the same as that of the satellite. An atom, under such conditions, would very soon cease to exist.

But atoms live on. Electrons should not be giving up energy and should not emit light. But bodies do emit light when heated!

The Biography of the Atom Written by Niels Bohr

Classical physics was again at an impasse. And a worse one than might be supposed. It was not able to account for the luminescence of heated bodies, and it could not explain the existence of spectra.

You remember the rag with the sodium chloride solution. The spectrum of this salt consists of only one yellow line, which means that the radiation of its atoms consists of only one wavelength.

Even if we assume that this line is emitted by an electron decelerated in the atom, we are immediately confronted by another difficulty. The laws of classical physics state that such an electron should emit not one line but a whole spectrum of lines with all wavelengths, and with no discontinuities in the spectrum. The spectrum of an electron should not differ from the spectrum of the sun. Yet we have only one yellow line!

Bohr realized that something was wrong. But what? Maybe the Rutherford model of the atom was to blame? No, it was too early to reject this model. And Bohr's teacher, Ernest Rutherford, was of the same opinion. It was thought an attempt should be made to modify and improve the model so that an electron in it could revolve about the nucleus and emit light and yet not fall onto the nucleus.

The year was 1912. Fresh in the memories of all physicists was the sensation that Einstein had created with his photons. And only three years before, it was Einstein again who completed his theory of relativity – another sensation. Naturally, all these attacks on classical physics could not but stir up the young physicists and add boldness to their mode of thinking.

Bohr continued to mull over the problem and at last got an idea. Why should an electron in an atom emit light continuously? Because it is always moving at an accelerated rate? Let's reject that and say that an electron in an atom need not give off light even when in accelerated motion.

And how is this possible? The electron has to move along a specific path about the nucleus, in an orbit, and not just any way. If the electron does not emit light, it can live in the atom as long as it likes.

But there was no way in which classical physics could countenance such a situation. What is more, it didn't follow from any other theory. Bohr was not able to prove it. And so he modestly called it a postulate. Bohr, incidentally, was never able to prove it within the framework of his theory. The proof came some ten years later and was quite unexpected. That we'll discuss later on. But how many possible orbits are there in which an electron can move without emitting light? Bohr's calculations show that the number is great, very great. What's the distinguishing feature? The mean distance from the nucleus: there are close orbits and distant orbits. Yet it is not a question of distance, but of the energy which the electron possesses in its orbit. Which is understandable, because the closer an electron is to the nucleus, the faster it has to move to keep from falling onto the nucleus. The reverse is true of a more distant electron, which is not so strongly attracted to the nucleus, and hence can move more slowly. The conclusion, then, is that the pathways (orbits) of electrons differ as to electron energy. As long as an electron stays in its orbit, there is no emission of light. Bohr at this point advanced a second postulate. Let us suppose an electron in orbit suddenly jumps to another orbit of less energy. Where has the excess energy gone? Energy cannot simply vanish away into nothing. Seek it outside the atom, says Bohr.

The energy is ejected from the atom in the form of a quantum, that same quantum of light energy which Einstein had introduced.

An electron that has emitted a photon takes up a different orbit and does not emit light any more. The photon is ejected during the minute fraction of time when it jumps from one orbit to the other.

Meanwhile the photon is making its way through the other atoms and finally gets out of the substance. It can enter our eye, it can be passed through a glass prism in a spectroscope and photographed. The energy contained in photons is transformed many times before we see its actual image as a black line on a photographic plate.

This line has a lot to say for itself. By measuring its position on the plate we can find the wavelength of the photon and its frequency. Then we take the Planck relationship between frequency and energy of photons and determine the energy of the photon. This energy comes out as the exact difference in energy between the old and new orbits in the atom. The blackness on the plate at the site of the spectral line indicates the number of photons there: the more there are, the blacker the line. The more photons, the brighter the body that has emitted them.

What a simple and elegant explanation of spectra. All the atoms of a certain substance are exactly alike. Hence, the electrons all exist under the same conditions. And so the photons emitted during jumps between two orbits are all the same. All transitions that electrons make between two orbits yield, in the final analysis, a single unique spectral line.

We have already mentioned that there are quite a few such old and new orbits. An electron can reside in any one of them, in turn.

Every jump from a higher-energy orbit to one of lower energy is accompanied by the birth of a photon. But since there is a difference of energy between different orbits, the photons will have different energies and frequencies. A photographic plate will then exhibit a series of narrow spectral lines. This is exactly what the spectrum of gaseous hydrogen looks like. It has several tens of lines with different wavelengths.

Generally speaking, such a simple spectrum as that of sodium consisting of only one line is a rarity. Spectra usually have many tens of lines and frequently even thousands of lines. The spectral patterns of some chemical compounds are so intricate that there doesn't seem to be any hope of disentangling them. But there are laws to go by which make the task easy.

Before Bohr's theory, physicists had racked their brains in attempts to decipher some of the complicated spectra. And when Bohr proved that the spectrum is the biography of the atom, more precisely, of the atomic electrons, the job was greatly simplified. All one had to do was to combine the various electron orbits in an atom until he obtained the observed lines of the spectrum.

And conversely, by examining a spectrum, one can draw all manner of conclusions about the conditions under which atomic electrons exist. This is very important. Actually, just about all that we know about the electron shells of atoms has been acquired through a painstaking analysis of their spectra.

From Where do We Reckon the Energy?

Now that Bohr has explained how an atom emits light, let us ask WHY. Why do bodies begin to emit light only at high temperatures and why do they cease to emit light at room temperature?

Before answering this question we shall have to digress a bit. The very convincing picture of the atom which we have just drawn will have to be turned upside down. Not that there is something wrong with it. No! It is simply the sequence of electron orbits that has to be reversed.

We considered the close orbits to be the most energetic ones, whence it followed that a photon was emitted when an electron jumped to an outer orbit from the nucleus. Actually, it is just the other way around.

Let us try to picture this business by digging a hole in the ground. Put a ball at the bottom of the hole and put another one on the ground near the hole. Which of the two balls has the greater energy?

A knowledgeable person will immediately say: "The question is not clear. First, what energy are you talking about, potential or kinetic? Second, from what level do you reckon the potential energy? If the level of the earth is taken, then the potential energy of the ball on the ground may be taken as zero, then the ball in the hole will have a potential energy less than zero, that is, negative energy. But if we reckon the potential energy from the bottom of the hole, then the ball on the ground will have a potential energy greater than zero. Since both balls are stationary, their kinetic energy in both cases is zero." Let's try the first frame of reference.

But suppose the ball is in motion. Then to its potential energy we add the kinetic energy. However, the sum of both energies, called the total energy, will obviously remain negative if the ball does not jump out of the hole. On the contrary, it will become positive if the ball jumps up and rolls along the ground.

This lengthy explanation may be a bit tiring to the reader but it will help to clarify many things now and later. The point is that from the viewpoint of energy, an electron in an atom is like the ball in the hole. A free, independent, electron is like the ball on the ground. Physicists have agreed to reckon the energy of such electrons taking for zero the total energy of a free but stationary electron.

Of course, there isn't very much in common between an electron and a ball. Probably only that they are both constrained in their movements. The ball can't, of itself, leave the hole, and an electron cannot leave its atom. That is precisely why atoms exist.

The closer the ball is to the top of the hole, the farther it is from the bottom and the greater its total energy (which means, the lower the negative value of energy). The same with the electron. The farther it is from the nucleus, the higher its total energy; the closer it is to the nucleus, the lower its energy (but the greater its negative value, naturally).

To summarize, then, when an electron jumps to an orbit closer to the nucleus, it diminishes its energy, so that photons are emitted in just such transitions. And conversely, the farther the orbit is from the nucleus, the closer the electron is to 'escaping' from the atom, and the more energy the electron has. Now let us return to our story.

Excited Atoms

Again we have to deal with our ball. Why doesn't it fall? Which is a silly question, since there is nowhere to fall.

We have a similar situation with an atomic electron at low temperatures. There is nowhere to jump to. The electron is located in the orbit closest to the nucleus; from here the only place to fall is onto the nucleus, which is just as impossible as for our ball to fall through the earth.

The electron energy is at its lowest. The electron has nothing left to lose. Therefore, it cannot emit any light.

It is evident that the electron must first be in an orbit some distance from the nucleus so as to be able to fall closer to the nucleus. The question is: How does the electron get into an outer orbit? The same way that a ball can get to the top of a ladder, say: by us putting it there, which is to say, by giving it some energy.

The same thing goes for the electron. To put it into a distant orbit, we must give it some energy. More specifically, we have to impart to the electron a portion of energy that is at least as much as the energy difference between the two orbits.

There are different ways of delivering the energy. One common way occurs in the thermal motion of atoms when one atom with sufficient speed collides with another, giving up the right amount of energy. At room temperature, such collisions are common, but the energy is too low. When the temperature reaches hundreds and thousands of degrees, collisions result in big exchanges of energy, electrons jump to new orbits, and light is emitted.

Energy has been imparted, the electron is in an outer orbit. Then what happens? The nucleus does not allow the electron to stay in the outer orbit for any length of time. It pulls it back into an inner orbit, and as the electron jumps inwards, a photon is ejected. Our eye perceives the photon and we say that the body glows, or emits light.

The body is now emitting light. Let us raise the temperature and see what happens. The thermal motion of the atoms becomes more energetic, collisions are more frequent and violent. The electron spends only a little time in its innermost orbit. The atoms more and more frequently go into a state which physicists call 'excited', then return to 'normal' only to leave it again almost immediately.

At this point, photons are being generated by thousands and millions every second. They build up avalanche-like as the temperature rises (recall the Stefan-Boltzmann law).

But it is not only the number of photons that is increasing. The lengths of the electron jumps also increase. The first timid jumps to neighbouring orbits and back again give way to record leaps to distant orbits, far away from the nucleus. Jumping back from such orbits the electrons generate very strong photons. And we know that the higher the energy of a photon, the greater its frequency and the smaller its wavelength. The emitted light becomes brighter and more 'violet' (recall Wien's displacement law).

Bohr's theory was thus able to account at one stroke for the basic laws of the theory of thermal radiation and spectroscopy. After this great success, the quantum nature of light and of atomic processes was obvious. In just a little while this was recognized by most scientists.

The First Setbacks

Yet it was still early to speak of a complete victory for Bohr's theory. The next ten years saw a tremendous development of the theory. There was a great expansion in the range of phenomena that it embraced. These included the most subtle processes of emission and absorption of light by atoms, and the detailed structure of atoms and molecules. In 1914, Kossel laid the foundations of quantum chemistry now included in every textbook on the subject. In 1916, Sommerfeld advanced a more exact theory of the origin of atomic spectra. To this day it helps decipher complicated spectra. The new theory was able to account for recently discovered magnetic and electrical properties of atoms and molecules.

At the same time, the Bohr theory was encountering more and more difficulties. It was not capable of explaining many new facts, some of which were the ones that gave it birth.

The first was in the very spectra that Bohr's theory helped to explain. The trouble was that the explanation was not sufficient.

We have already mentioned that spectral lines are characterized not only by wavelength but by brightness too. From Bohr's theory we could find the distance between the rungs of the energy ladder of electron orbits (that is, the wavelengths of the photons generated in electron jumps from rung to rung, from orbit to orbit). But the theory was helpless as far as accounting for the brightness of the spectral lines was concerned.

It was not clear how one could calculate the number of photons in the spectrum.

It was obviously too early to speak of a victory for the Bohr theory over classical physics. Though he at first dispensed with the classics, he later had to revert to them. This was in the form of the so-called correspondence principle.

In a nutshell it was this. Classical physics was able to calculate the brightness of spectra, but could not account for their origin. Quantum mechanics was able to explain the essence of spectra, but could not calculate the brightness of the spectral lines. Bohr concluded that both theories had to be used, and that they should be harnessed together in areas where they more or less coincided.

But where did this occur? According to classical physics, an electron in orbit about an atomic nucleus would come closer and closer to it and finally fall onto it. In the process, it would emit a continuous spectrum with no single lines.

According to quantum mechanics, an electron in an atom radiates separate lines or, as we say, radiates a discrete spectrum. What have the two spectra in common?

The rungs of the energy ladder of electron orbits have different heights. The height is less, the farther the orbit is from the nucleus. The energy ladder in the atom is somewhat like a long ladder looked at endwise, in perspective, so to speak: the rungs at the far end appear close together. In the case of the ladder, this is simply an optical illusion, while in the atom it is an actual fact.

But the height of the energy level corresponds to the energy of the photon or the wavelength of its spectral line. Thus, long wavelength lines of the spectrum, which correspond to electron jumps between orbits distant from the nucleus, must be close to one another, which makes it appear as an almost continuous spectrum.

Thus, the long wavelength section of the 'quantum' spectrum should not differ materially from the very same section of the 'classical' spectrum. In this region, the brightness of the first spectrum could be calculated on the basis of classical physics. And then we could extend the calculation to the entire 'quantum' spectrum. That is the correspondence principle.

It was a brilliant idea, only in practice physicists were disappointed. Experiment yielded line brightnesses that differed from those of theory.

Generally speaking, it was hard to expect anything else. A theory that has to resort to outside help is not very strong. And one that has to go for help to its recent opponent is weak indeed.

To introduce classical physics into quantum mechanics is, as the English physicist Bragg once said, like preaching 'classical religion' on even days of the week and 'quantum religion' on odd days. Though science sometimes resorts to two gods and finds it useful, actually it is an indication of a weakness in the theory.

A closer look at the new theory will show that the correspondence principle was not the only lapse in Bohr's theory. Actually, from the very start all its basic premises bore clear traces of classical physics.

Bohr rejected the classical views on electron motion, yet introduced the concept of electron orbits in the atom. He was firmly convinced that electrons revolved about the nucleus of the atom in the same way that the earth moves round the sun.

Bohr 'prohibited' the electron from radiating while in orbit, but he could not find any good justification for doing so. Bohr's theory gave a correct explanation of the origin of photons in atoms, but the process as such remained a mystery. It did not follow from any of its postulates.

This dual nature of Bohr's theory was quick to manifest itself. New facts cropped up that did not fit into the framework of the theory. Yet it had merits. Bohr's theory was a tremendous step forward in understanding the world of the atom. And it had its limitations. It explained much that was incomprehensible and beyond the means of classical physics. But almost as much remained unaccounted for.

The time for new steps had come. And they were soon made. The first was taken by the French physicist Louis de Broglie.

From Bohr's theory to quantum mechanics

A Remarkable Article

In 1924, the September issue of the English "Philosophical Magazine" carried an article by an unknown physicist, Louis de Broglie. The author described the principal points of his dissertation, which was devoted to the possible existence of matter waves.

Waves of matter? Weren't they the commonly known sound, light and other such waves, which are quite material and which are perceived by our sense organs or are recorded by instruments?

No, it turns out that de Broglie had in mind quite different waves. The views expressed by de Broglie were so unorthodox and paradoxical that they could easily compete in originality with those put forward by Planck a quarter of a century before concerning quanta of energy. And not only as to their importance to physics, but also in the way they were received by very many physicists: open incredulity.

What are these matter waves, anyway?

Before going into item, let us take a look at 'ordinary' waves, which had been thoroughly studied by that time.

A Little about Ordinary Waves

Throw a stone into a pond and watch the waves move over the surface of the water. Incidentally, surface waves are practically the only type of wave that can be observed directly in motion.

It might appear that the water itself moves with the waves. But this is not so. Watch any little boy throw stones behind his toy ship hoping in this way to move it back to the shore. The waves move under the craft, which just bobs up and down in one place. This means that the water does not move away, but just up and down. In big waves produced by big stones, there is a little movement of the water, but never for any great distance.

This 'carrying' property of high surface waves is made use of in riding the surf, a sport common in Australia and the Hawaiian islands. The sportsman stands on a large board and moves up and down with the big regular waves moving in towards the shore. He gets onto a wave and moves towards the shore at a tremendous speed. But the slightest false move and he will find himself in the trough of the wave instead of on the crest.

In this risky, exciting sport, the wave carries the sportsman piloting him towards the shore. Remember the term, pilot wave. We shall return to it later on.

Last century, physicists learned that sound was also a wave motion. Sound waves were found to be propagated in the air, in water, and in solids. What is it that vibrates in sound waves? The particles of the medium through which the sound is propagated. Molecules of air, water, the atoms of solids.

Take away the air, water, matter generally, and sound waves disappear. There is no sound in a void. Future astronauts will probably observe grandiose eruptions of volcanoes on distant airless planets all in complete silence. Only the ground shaking under their feet will be felt. On the moon, spacecraft will start up in absolute silence. There will be no roar of rocket engines as we know it here on earth.

The physicists of last century likewise learned about the nature of electromagnetic waves produced by the movement of electric charges.

The light and radiowaves of distant stars and nebulae now arriving at the earth began their trip thousands and millions of years ago. Their pathways lay mostly through enormous and nearly empty interstellar spaces. On the moon, astronauts in complete silence will watch jets of dazzling fire eject from the bottom of their space rocket.

In a vacuum, one can see and not hear. That is the most fundamental difference between electromagnetic waves and mechanical waves, including sound waves. No intermediate medium is needed for the propagation of electromagnetic waves. On the contrary, a medium only reduces their speed.

Getting Acquainted with Matter Waves

Let us return to the matter waves.

De Broglie maintained that these waves are generated in the motion of any body, whether a planet, a stone, a particle of dust or an electron. Like electromagnetic waves, they are capable of propagation in an absolute void. Hence, they are not mechanical waves. But they are produced in the motion of all bodies, including those not charged electrically. Hence, they are not electromagnetic waves.

At that time physicists did not know of any other kinds of waves. So matter waves were indeed some sort of new hitherto unknown waves. Utter nonsense, said the older physicists with a shrug.

They were firmly convinced that all possible waves had already been discovered. This young Louis de Broglie speaks of waves of matter; but are not mechanical and electromagnetic waves, waves of matter? Without matter there are no waves, in fact there is nothing at all!

True, de Broglie didn't think up a very good name for his waves. But what could he do? New things get names before scientists have time to understand them properly.

That is exactly what happened to de Broglie. Those matter waves of his proved so intricate that physicists are still arguing about them. We shall have to take a closer look at the de Broglie waves because they are the foundation of present-day quantum mechanics.

Why Can't We See de Broglie Waves?

That was probably one of the first questions that physicists asked de Broglie. Well, how do we generally perceive waves? Not only by means of our sense organs, which are a rather poor instrument anyway. The human ear perceives sound waves with frequencies between 20 and 16,000 vibrations per second. These frequencies correspond to sound wavelengths in air of about 17 metres to 2 centimetres. The human eye reacts to light waves of length from 0.4 to 0.8 micron. Those are nature's 'windows' as far as learning about waves goes (if, of course, we leave out the surface waves of the sea).

Physicists use special instruments to transform waves beyond the human range to lengths that lie within these two 'windows'. This greatly extends our possibilities of studying wave phenomena. Radio receiving sets pick up and allow us to study radiowaves of the metre and centimetre band that come to earth from the depths of the universe. Scintillation counters* enable us to detect gamma rays emitted by atomic nuclei. These are electromagnetic waves millionths of millionths of a millimetre long.

It is now clear that the range of wavelengths that have been studied is very great. Why, then, haven't we been able to detect the de Broglie waves?

The point is: How? Mechanical waves (sound waves, for instance) metres in length can be detected by the ear. But a radio, even when tuned to the given wavelength, cannot detect them. The radio responds only to radiowaves. And, looking at it from another angle, radiowaves are not perceived by the human ear or any other mechanical instrument, even if they are several metres in length.

Each type of receiver responds only to its specific type of wave. The ear responds to sound waves, the eye to electromagnetic waves. How does one detect de Broglie waves, since they don't belong to either class? Actually, that is the answer to the question we started out with. Later on we will learn more about this.

We get another answer if we try to determine the wavelength of these matter waves. De Broglie obtained a relationship connecting the length of the new waves with the mass and velocity of moving bodies. Here's

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* Scintillation counters use special crystals for registering nuclear particles and gamma quanta. When a particle or quantum of radiation impinges on such a crystal, a flash, or scintillation, is emitted and recorded by sensitive instruments.

what it looks like:

$$\lambda = \frac{h}{mv}$$

In this relation, lambda (λ) denotes the de Broglie wavelength, and m and v are, respectively, the mass and velocity of the body; h is our old friend, the Planck constant.

This is significant because it means that the de Broglie waves are of a quantum nature. We shall take up this question again later on. Meanwhile, let us find out what wavelengths correspond, according to de Broglie, to the motion of objects about us. Let us calculate briefly for a planet, a stone and an electron.

Just a glance will show that these wavelengths should be extremely small, since the numerator is Planck's constant, which is exceedingly small: 6.6×10^{-27} erg per second.

Let us take the planet earth. It has a mass of 6×10^{27} grams and a velocity of orbital motion about the sun roughly 3×10^{6} cm/s. Putting these figures in the de Broglie relation, we find the length of the earth wave to be

$$\lambda = \frac{6.6 \times 10^{-27}}{6 \times 10^{27} \times 3 \times 10^{6}} = 3.6 \times 10^{-61} \text{ cm}$$

That is fantastically small. No existing or foreseeable instruments could record anything that small. There just doesn't seem to be any comparison to illustrate just how very small this figure is.

Let us see what the wavelength of a stone is like. Take a stone of 100 grams travelling at a speed of 100 cm a second. From de Broglie's formula we find

$$\lambda = \frac{6.6 \times 10^{-27}}{100 \times 100} = 6.6 \times 10^{-31} \text{ cm}$$

Not much better than the earth's de Broglie wavelength. Absolutely hopeless of ever being detected. It is a million, million, million times smaller than the atomic nucleus, which itself is far beyond the range of any microscope.

Now let us take the electron. It has a mass of about 10^{-27} gram. If an electron begins to move in an electric field with a potential difference of one volt, it will acquire a velocity of 6×10^7 centimetres per second. Putting these figures into the de Broglie relation gives us

$$\lambda = \frac{6.6 \times 10^{-27}}{6 \times 10^7 \times 10^{-27}} = 10^{-7} \text{ cm}$$

This is something quite different. 10^{-7} cm corresponds approximately to the wavelengths of X-rays, which can be detected. Thus, in principle, we should be able to detect a de Broglie electron wave.

The Wave is Found

But how? The de Broglie wave exists in theory and there doesn't seem to be any way of detecting it instrumentally. But a wave is a wave and there must be some phenomenon in which it will manifest itself no matter what its nature. An attempt was made to catch the de Broglie wave in a diffraction experiment, the point being that diffraction is so completely a wave phenomenon. Diffraction consists in the fact that when a wave encounters some obstacle it passes round it. In doing so, the wave is slightly deflected from its straight path and moves into the 'shadow' behind the obstacle.

The diffraction pattern of waves from a round obstacle or a round aperture in a screen opaque to waves is

X-ray pattern

Fig. 1

typically a system of alternate dark and light rings. Such a pattern is seen, for example, when one looks at a street lamp through a dusty glass. On frosty nights, the moon is surrounded by several light and dark rings: the moon light has experienced diffraction on minute ice crystals dancing in the air.

Diffraction is a definite indication of the existence of waves. It was precisely the discovery of the diffraction of light at the start of the nineteenth century that served as a most convincing argument for the wave theory of light.

But the wavelengths of light waves are hundreds and even thousands of times greater than those of the de Broglie waves of electrons. All the devices constructed for producing diffraction of light – slits, screens, diffraction gratings – were much too crude. The dimensions of the obstacles used to observe diffraction of a wave must be comparable with or less than the wavelength.

Electron diffraction pattern

Fig. 2

What is possible with light waves, is utterly out of the question when dealing with the de Broglie waves.

By 1924, it was known what objects to use in attempts to detect the diffraction of the de Broglie electron waves. Twelve years before, the German scientist Laue had noticed the diffraction of X-rays on crystals. Laue noticed a series of dark and light dots on a photographic plate exposed to X-rays that had passed through a crystal. Several years later, Debye and Scherer repeated Laue's experiment on small-crystal samples of powders, and obtained diffraction rings. In these cases, diffraction was possible because the distances between the atoms in the crystals (like slits in a 'screen' opaque to X-rays) were of the same order of magnitude as the wavelength of X-rays: 10^{-8} centimetre.

But the lengths of the de Broglie waves lie precisely within this range! Which means that if these waves do really exist, then electrons, in passing through a crystal, should produce the same diffraction pattern on a photographic plate as X-rays.

A few years after de Broglie advanced his new concept, the American scientists Davisson and Germer and the Soviet physicist P. Tartakovsky verified it in an experiment on the diffraction of electrons by a crystal.

However, in itself the analogy between the 'electron rays' and X-rays was not enough. The experiment required great ingenuity.

X-rays passed through the crystal almost unimpeded, while electrons were totally absorbed in a layer of crystal only a fraction of a millimetre thick. What was needed, therefore, was very thin crystal plates, or metal foils, or maybe to work with obstacles and not apertures. In this case, a beam of electrons was directed at a small angle to the face of the crystal so that the electrons sort of slid along it without going deep into the crystal and bouncing back. As a result, the electrons experienced diffraction only on atoms in the outermost layers of the crystal. The electrons that had experienced diffraction were recorded on photographic plates.*

Tartakovsky sent a beam of electrons onto a thin foil consisting of a multitude of minute crystals. The exposure was several minutes long.

When developed, the photograph exhibited the outlines of real diffraction rings. These first plates – worth more than their weight in gold – were sent to the largest physical laboratories of the world. There they were carefully scrutinized. There was no more doubt. De Broglie's bold hypothesis concerning matter waves was brilliantly confirmed by experiment. Electrons exhibit the properties of particles *and* the properties of waves!

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* Electrons can fog a photographic plate in the same way that visible light or X-rays do.

Two-Faced Particles

Even before these decisive experiments, scientists were trying to get at the real meaning of the de Broglie waves. How was one to understand this dual nature in the behaviour of particles, of electrons?

In those days, physicists knew what an electron was. A very small and very lightweight particle of matter carrying a minute electric charge. For a long time no one asked what shape this particle had or what occurred inside it. There was no way of actually observing an electron, to say nothing of trying to figure out its internal structure.

But if an electron is a particle, then it obviously must have the properties of a particle. How could an electron have the properties of waves, something so utterly different?

The first attempt to interpret matter waves was made by de Broglie himself. It clearly indicated that when physicists first entered the world of the ultrasmall they continued, from habit, to work with pictorial models. In the Bohr-Rutherford theory, the atom was like a planeraty system in which the electron planets revolved about a sun nucleus, the only difference being that, unlike planets, electrons could frequently change their orbits.

But then came the light quantum, the photon. As Einstein had shown, it too possessed the properties both of waves and of particles. Obviously, such a dual object was beyond any pictorial representation.

Thus physics was confronted by the first unrepresentable entity. Now, with de Broglie's discovery, this unimaginableness had to be extended to particles of matter, from the tiny electron to enormous astronomical bodies. This was truly something to recoil from.

How could one even imagine that an electron flying at an obstacle would, as a result of diffraction, move round and get behind it. No, waves and particles were two mutually exclusive entities. A thing was either a wave or a particle!

And yet the de Broglie waves existed. It was not 'either or' but 'both'. Something had to be done to connect the unconnectable. And not for the single specific case of a diffracting electron. If an electron has wave properties, then so inevitably do all the objects of our world, from the smallest to the biggest.

De Broglie suggested beginning this unusual synthesis with the concept of a pilot wave.

Pilot Waves

Let's go back to riding the surf. The rider gets on the crest of a high wave that carries him to the shore. The wave acts as a pilot.

De Broglie's idea is that matter waves pilot moving particles of matter in a similar fashion. A particle, as it were, sits on a wave and moves wherever the matter wave carries it.

The length of this wave, de Broglie says, may be very great. At small velocities of motion of an electron, the length of the electron wave is many thousands of times greater than the electron. As the velocity increases, the particle, as it were, pulls the wave into itself, and the wave becomes shorter. But even at high velocities of motion the length of an electron wave is still greater than the 'dimensions' of the electron itself.

It doesn't exactly matter who leads whom, the electron the wave or the wave the electron. The important thing is that the wave is connected with the electron intimately and for all time. The electron wave disappears only when the electron stops. At this instant the denominator in the de Broglie relationship becomes zero and the wavelength, infinity. In other words, the crest and trough of the wave move so far apart that the electron wave ceases to be a wave.

The de Broglie picture is quite vivid: an electron riding its own wave. But where did the wave come from? It exists with the particle even when the latter is in motion in an absolute void. Which means that the wave is generated only by the particle itself. And how does that occur?

De Broglie's hypothesis has nothing to say on that score. Well, maybe the hypothesis can explain what interaction there is between a particle and its wave, how the wave moves together with the particle, how it shares the fate of the particle in the latter's interactions with other particles and fields, for example, when particles are incident on an obstacle or on a photographic plate. No, the hypothesis does not offer any convincing explanation.

In the search for a way out, de Broglie tried to eliminate the particle altogether. Why not imagine the wave itself to be the particle? In other words, picture the particle as a compact formation of its waves, a wave packet, as it was called by physicists. A packet was to consist of a small number of rather short waves; when two or more packets collide they ought to behave like particles – exactly like a short-wave photon when it ejects an electron from a metal. But no matter how compact the packet, no matter how much it resembles a particle, it consists of waves. This surely means that there must be phenomena in which it will exhibit its primordial wave nature.

But nature rejected this proposal as well. It turned out that no matter how compact the wave packets are, they cannot form a particle. This is fundamentally impossible. The point is that these packets rapidly disintegrate in time, even in a total vacuum. In negligible intervals of time, a packet becomes so smeared out in space that the formerly compact particle is diluted to homeopathic proportions. Yet we know that particles are definitely stable, there is not a trace of any kind of spreading out in time.

This model too had to be given up. The mechanical combining of two such mutually exclusive entities as waves and particles into a single image was not a success. And it couldn't be. But that came later. De Broglie, however, did not want to give up his 'centaur' with the head of a particle and the body of a wave.

Two years passed. In the summer of 1927, physicists from all over the world arrived in Brussels at the Solvay Congress at which de Broglie's representation on the relationship between waves and particles was resoundingly rejected. For many years to come, a completely different representation of this relationship led the way. It was presented at the congress by two young German physicists, Werner Heisenberg and Erwin Schrödinger.

Together or Separately?

Heisenberg and Schrödinger buried the de Broglie conceptions, but spoke in doing so that this determined the whole subsequent development of quantum mechanics.

The principal idea of de Broglie concerning waves associated with the motion of bodies was quickly taken up by scientists in a number of countries. Hardly a year passed after de Broglie's first paper appeared when the German physicist Max Born proposed his own idea of the de Broglie waves.

Heisenberg, Born's pupil, who was just beginning his career in science, got interested in the problem. De Broglie's research was heatedly discussed by another group of physicists that included Schrödinger.

And then ... but we won't keep to the chronological order of events. The concluding episodes of a film shown at the beginning help to understand what is going on and heighten the dramatic effect.

Recall the experiment that proved the diffraction of electrons. In it an electron beam impinged on a crystal (or a very thin metal foil). The electrons of the beam experienced diffraction on the atoms of the crystal and impinged on a photographic plate fogging it and leaving diffraction rings.

We may now add that the electron beam produced by an incandescent metallic filament was specially formed. A diaphragm with a small circular aperture was inserted between the source and the crystal. As a result, after the electron beam had passed through the diaphragm it had definite cross-sectional dimensions.

What would have happened if we had stopped the experiment at the very start when there were only, say, several tens of electrons? When the photographic plate was developed we would see something like a target peppered with shot by an inexperienced rifleman. The dark dots correspond to the hits of separate electrons distributed over the plate quite at random.

Continuing the experiment, we would see a gradually emerging regularity in places where the electrons strike the target. After several thousand shots, the plate would reveal clearcut dark and light rings, which were actually detected by scientists.

This is an interesting fact. Obviously, as long as the number of electrons participating in diffraction is small, no wave properties are exhibited. These properties appear only for large numbers of electrons. In other words, the wave properties of particles seem to be manifested only by large assemblies.

To find the answer, we experiment again. The same experiment with diffraction of electrons but done differently. We can take a powerful source of electrons and expose a photographic plate for a short time. The diffraction pattern will then be formed quickly. Or we can take a weak source of electrons and lengthen the exposure time. But if in both cases the same number of electrons impinge on the plate, absolutely identical diffraction patterns will be produced.

This is very important. In the first case, when the electrons experience diffraction on the crystal all at once, one can speak of something in the nature of an assembly. But in the second case, when the electrons impinge on the crystal individually, the concept of an assembly is hardly applicable. What kind of a team of railway workers would you have if one welded one day, another moved a bolt the next day, and a third tightened it a month later?

The pattern is the same when the electrons undergo diffraction thousands at a time, and when they do it one at a time. The conclusion is obvious: each of the electrons displays its unusual properties independently of the others as if no other electrons existed at all.

A Visit to the Shooting Range

Let's take the target we spoiled. It was produced by a small number of electrons. At first glance, it would appear that the electrons impinged on the plate utterly at random.

But there is one thing that attracts our attention. We measure the aperture in the diaphragm from which the electrons emerged and project the outline onto the target. It would seem that all the electrons should fit inside this outline, no matter how randomly they had fallen on the photographic plate. Actually, however, many of the hits are far outside the boundary line.

And here is another interesting thing. If we examine the target carefully, it will be noticed that the electrons do not strike the plate in random fashion at all. Even when the number of hits on the target is small, there are blank places with not a single hit and there are closely bunched groups of hits. If a line is drawn through these places, little rings appear.

True, they are not well defined, but they improve as the number of electrons striking the plate increases.

Let's play a trick. Take an ordinary rifle target and punch holes where the electrons hit the photographic plate. Then show the target to a real marksman and see what his reaction is.

"What a funny way to shoot. Look at all those hits in number 10, and not a single one in 9 or 8. Was that done on purpose? All in 10, 7, 4 and 1?"

We don't say anything, and after a short while the chief marksman says, "Nonsense! No one could ever shoot up a target that way, no matter how he tried. And here's why. If the man is a beginner, his hits will lie at random, more or less evenly distributed over the whole target. The target of an experienced marksman looks quite different: a lot grouped around the bull's eye and just a few in the outer rings. Let's count the total number of hits in each ring of the target and construct a graph.