# THE NATURE AND DEVELOPMENT OF MODERN PHYSICS

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RHODES UNIVERSITY

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# THE NATURE AND DEVELOPMENT OF MODERN PHYSICS.

The development of modern physics is one of the greatest of man's intellectual achievements to date. Its magnitude is not always fully recognised, and when recognition is accorded, it is often given in ignorance of the nature or value of what has been accomplished.

Too often the student of the humanities confuses science with technology and takes pride in his ignorance of both. He may be fluent in the language of the ancient Greeks, and be familiar with the primitive scientific concepts of Plato and Aristotle. He remains ignorant of mathematics, the language of modern physics, and hence knows nothing of the scientific concepts of Einstein, Schrödinger and Dirac.

On the other hand there is the moral philosopher or theologian, who is ever ready to borrow some phrase like "indeterminacy" or "relativity" from physical science, and proceed to discuss and criticise this outside its physical context. The nature of physics then becomes obscured with concepts like "free-will" and "absolute truth" which are not within its orbit.

Physics is neither crude technology nor speculative philosophy. My counterpart in the Scottish Universities is known as the "professor of natural philosophy". At Oxford he is the "professor of experimental philosophy".

Both titles reveal clearly the nature of physics — the philosophy of natural things, philosophy based on experiment.

Experiment is the foundation of modern physics. In the words of Leonardo da Vinci "Experiments never deceive. It is our judgment which sometimes deceives itself because it expects results which experiment refuses. We must consult experiment, varying the circumstances until we have deduced reliable rules".

"We must consult experiment until we have deduced reliable rules". Modern physics is the product of this integration of experiment and theory. The dangers of divorcing the two approaches were pointed out by Dr. Johnson: "The philosopher may be delighted with the extent of his views, the artificer with the readiness of his hands, but let the one remember that without mechanical performance, refined speculation is an empty dream, and the other that without theoretical reasoning, dexterity is little more than a brute instinct."

I propose in this lecture to trace briefly the development of man's ideas about the basic problem of physics, the structure of matter, a problem over which man has puzzled from the earliest times.

Aristotle considered matter to consist of four elements: earth, air, water and fire. The Greeks had a love of geometry, and sought to interpret the entire physical universe in geometrical terms. Thus Plato proposed that the earth was composed of cubes, the air of regular octahedra, water of regular icosahedra, fire of regular pyramids, and the human body of triangles. There is a superficial resemblance between this geometrical hypothesis, and the beautiful atomic patterns of matter revealed by modern X-ray crystallography, but Plato's speculations lack any physical value or experimental validity.

Another of the Greek philosophers, Democritus, suggested that all matter was composed of moving atoms. Despite the apparent modernity of this view, the type of reasoning on which such conjecture was based can best be illustrated by a quotation from one of his Roman followers, Lucretius.

*"How different is fire from piercing frost,*
*Yet both composed of atoms toothed and sharp*
*As proven by touch . . . .*
*How different then must forms of atoms be*
*Which such sensations varied can produce."*

This type of idle speculation, inherited from the Greeks, poisoned the development of scientific thought until the 17th century. It was then that Galileo, who is regarded as the father of modern physics, subjected many of these speculations to experimental test and showed them to be false. Nevertheless he was opposed by the full authority and dogma of the philosophers and the Church, and was later forced to recant. In a letter to Kepler, Galileo revealed the stupidity and prejudice of this opposition to his astronomical discoveries:

"Oh, my dear Kepler, how I wish that we could have one hearty laugh together. Here, at Padua, is the principal professor of philosophy, whom I have repeatedly and urgently requested to look at the moon and the planets through my glass, which he pertinaceously refuses to do. Why are you not here? what shouts of laughter we should have at this glorious folly. And to hear the professor of philosophy at Pisa labouring before the Grand Duke with logical arguments, as if with magical incantations to charm the new planets out of the sky".

Here is the type of argument used by the philosophers of the day to explain away Galileo's discovery of the four satellites of Jupiter:

"These satellites of Jupiter are invisible to the naked eye, and therefore can have no influence on the earth, and therefore would be useless, and therefore do not exist."

The astronomical observations of Galileo and his contemporaries Tycho Brahe and Kepler, provided valuable experimental data for Newton, who was born in the year after Galileo's death. Newton saw clearly that all matter possessed one common definable property, that of mass. He distinguished this property of mass from that of weight, which is the force exerted by the gravitational attraction of the earth on the mass. Weight varies with position, mass is constant. Newton's theory of universal gravitation, that mass attracts mass, and that the force between the two masses varies as the inverse square of the distance between them, was not a mere speculation, but a mathematical theory deduced from experimental observations. The laws of motion of matter, formulated by Newton, form the basis for the whole science of mechanics. Although these laws tell us nothing of the nature of matter, except that it possesses the general property of mass, they describe its universal behaviour.

A century later Dalton proposed the atomic theory of matter. Dalton was a mathematician and it is believed that the theory was suggested to him by one of the propositions in Newton's "Principia". Unlike Democritus' speculations, Dalton's theory was based on experiment. From measurements of the relative proportions by weight (or mass) of the different elements in a chemical compound, he proposed that all substances consist of molecules, and that these molecules are built up of atoms of a relatively few elements. The distinguishing property of the different types of atoms is not some hypothetical cubical, octahedral or tetrahedral shape, but their relative mass. Dalton's atomic theory forms the basis for modern chemistry. It enables the structure of the hundreds of thousands of different forms of matter to be described in terms of less than 100 different atoms.

Nearly another century elapsed before the structure of the atom itself was investigated. In 1897 J. J. Thomson discovered experimentally a particle, which has only about 1/2000th of the mass of the lightest atom. This subatomic particle known as the electron, is a universal constituent of all atoms. Apart from its mass, the electron has a single unit of negative electrical charge, the smallest unit that can exist, since electricity like matter is found to be atomic in nature. In 1912 Rutherford and Bohr proposed a nuclear theory of the atom, based on the new experimental data in the field of atomic physics. The Bohr-Rutherford atom consists of a small central nucleus, containing most of the mass, surrounded by a swarm of electrons, rotating in orbits. The atom is like a miniature solar system, with the nucleus as the sun, and the electrons as the planets. The number of electrons in the atom distinguishes its chemical nature, from the single electron of hydrogen, to the 92 electrons of uranium. The arrangement of these electrons into different energy levels, using the exclusion principle of Pauli, explains in a beautiful manner the chemical behaviour of the different atoms, and their characteristic spectra.

The nucleus is built up of two different types of particle, the proton and the neutron. The proton is the nucleus of the lightest atom, hydrogen, and has a single positive electrical charge, equal and opposite to that of the electron. The neutron discovered by Chadwick in 1932, has a similar mass to the proton, but it is uncharged. Each different nucleus contains a certain number of protons and neutrons, the total number of particles being equal to the atomic mass, relative to hydrogen with its single proton. The total number of protons gives the nuclear charge, or atomic number as it is called, which in turn is equal to the number of orbital electrons. Thus on the Bohr-Rutherford model, the structure of all atoms and hence of all matter is described in terms of three fundamental particles, the electron, the proton and the neutron. Atomic structure is reduced to simple arithmetic, for we see for example that the atom of Uranium of mass 238, atomic number 92, consists of 92 electrons, 92 protons and $(238 - 92) = 146$ neutrons. The physicist had achieved his simplest description of the structure of matter ever.

But the advent of atomic and nuclear physics brought other concepts about the structure of matter, and raised fresh questions about these entities called "mass" and "particle", I can only refer briefly to some of these questions.

Newtonian mechanics was shown to be valid only for particles moving with velocities small compared with the velocity of light. The more general relativistic mechanics, developed by Einstein indicates that the mass of a very fast-moving particle is not contant, but increases with velocity. Expressed mathematically,

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

where $m$ is the mass of a particle with velocity $v$, $c$ is the velocity of light, and $m_0$ is the mass of the particle at rest. This dependence of mass on velocity has been verified experimentally using beams of electrons.

A further result of relativistic mechanics is that mass and energy can no longer be considered as distinct entities, but are equivalent, the energy $E$ of a particle of rest-mass $m_0$ being

$$E = m_0c^2$$

The earlier principles of the conservation of energy and mass are replaced by a more general principle, the conservation of mass-energy. Again this theoretical result has been verified experimentally.

Physical phenomena have been observed in which elementary particles are "annihilated". The inverse process of "materialisation", the conversion of energy into mass, also occurs. The immense energy liberated in an atomic bomb explosion comes from the conversion of a small fraction of the mass of the reacting plutonium into energy.

Energy can exist independently of matter, in the form of radiation. Our knowledge of the nature of radiation has been developed in similar manner to that of the nature of matter, which I have described. Visible radiation or light was initially studied and shown experimentally, from diffraction and interference effects, to consist of waves. It has been observed for example that when a beam of light is passed through a small pin-hole, the bright central spot is surrounded by a number of weaker concentric rings. This type of diffraction effect is characteristic of a wave phenomenon. Subsequently Maxwell showed that these waves consisted of electro-magnetic vibrations. Electromagnetic radiation is not restricted to the visible region, but extends over a very wide spectrum from the low-frequency radio waves, through the microwave region, the infra-red, visible and ultra-violet radiations, into the very high frequency X-rays and $\gamma$-rays emitted by atoms and their nuclei.

All electromagnetic waves travel through free space with the same velocity $c$ of 300 million metres/second, but the nature of the radiation is determined by the characteristic frequency $\nu$, the number of electromagnetic vibrations per second.

Thus it might seem that a description could be given of the physical universe in terms of the two entities, expressed variously as matter and radiation, or as mass and energy, or as particles and waves. So it appeared until Planck put forward his quantum theory, that radiation is not continuous but consists of small particles of energy, called quanta or photons, given by

$$E = h\nu$$

where $h$ is the universal Planck's constant. The quantum theory was confirmed from experimental observations on photons, and their interaction with matter. Thus we have what has sometimes been called the dual nature of radiation. One popular scientific writer has suggested that: "On Mondays, Wednesdays and Fridays radiation acts like waves, and on Tuesdays, Thursdays and Saturdays it acts like particles." Sunday is presumably the day of rest.

Ignoring the cynicism, and confining ourselves to the experimental data, we find that radiation behaves individually as photons, and collectively as waves, the common property of frequency providing the link between the two types of behaviour.

This dual property of radiation led de Broglie to propose that matter, which we have seen to behave individually as particles, might also behave collectively as waves. This brilliant inspiration was confirmed by the experiments of G. P. Thomson, who observed diffraction effects with beams of electrons similar to those produced by beams of light.

Physics has advanced a long way in the last 40 years, since the simple Bohr-Rutherford model of the atom. This model with its three fundamental particles, the electron, proton and neutron, with their elementary properties of mass and charge, represents now only a brilliant simplification of nature, a physical model embodying some of the experimental facts.

The particles must now be expressed not as single point entities, but as waves of density or of probability, and for this the new mathematics of wave mechanics has been developed by Schrödinger and Dirac. Those who seek a model of the atom to-day must be content with a set of complex mathematical equations describing these properties. The seeker after knowledge is met with the same words that Plato had inscribed over his Academy in ancient Athens: "*Let no one without mathematics enter.*"

And as if to obtain his revenge on the theorist for turning the atom into a mathematical monastery, the experimentalist has returned to his laboratory and proceeded to discover over the course of the last few years about a dozen new fundamental particles, positrons, neutrinos and various types of mesons, most of which the theorists find redundant to their present scheme of things. To-day as always in a healthy science, we know far more questions than we know answers. At the end of his life Newton said "To myself I seem to have been only like a boy playing on the seashore and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean truth lay all undiscovered before me" and he added "New truths unfold themselves with the years, grander and ampler principles are revealed, but after each discovery the great ocean still stretches out, illimitable in its immensities, until it seems to mingle with the heavens".