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ELEMENTARY PARTICLES IN THE SERVICE OF MAN

The following article was prepared by R. M. Longstaff of the Wantage Research Laboratory in connection with the exhibit on "Elementary Particles", staged at the Physics Exhibition in March, 1966, jointly by the Rutherford Laboratory and the Atomic Energy Research Establishment.

INTRODUCTION

The fundamental building bricks of the universe have from time immemorial provided a fruitful field for speculation and, since the beginning of experimental science, for research. At the present time researches into the structure of the atomic nucleus and of the forces that hold it together constitute a major activity of "big science" and employ a substantial proportion, in man-power and equipment, of the world's research effort in the whole field of physics. This is a far cry from the situation only a few decades ago when the efforts of individuals, often working in primitive conditions and on a shoe-string budget, pioneered the field with the establishment first of the existence of the electron as a constituent of all matter, and later of the fact that atoms have nuclei and that these nuclei consist of protons and neutrons. Now some of the world's most expensive research tools are being used in establishing order amid the apparent welter of so-called "elementary" particles.

Some of the practical developments in technology and medicine which have resulted from, or have been notably aided by, our understanding of these matters are described in this article. Most of the material will be familiar, and much has inevitably been left out - photons, for example, are entirely omitted for lack of adequate space in which to do them justice - but it is hoped that a useful picture is presented, particularly for those teaching science in schools.

USEFUL PARTICLES

Of all the elementary particles so far discovered and classified only a very few have hitherto found any practical use outside their natural role as basic constituents of matter, or in fields other than scientific research: these are the electron, its opposite number the positron, the proton and the neutron; one other, the negative π-meson, shows promise of joining this small band of "useful" particles. There is little doubt however that practical developments will arise which will make use of other particles besides these. If photons of electromagnetic radiation are to be regarded as particles - as certain of their characteristics qualify them to be, especially in the higher energy ranges - then practically the whole spectrum from gamma rays to the longest radio waves could be included.

THE ELECTRON

Overwhelmingly the most important and versatile of the elementary particles from the point of view of practical applications is of course the electron. It is convenient to classify its role in practical affairs according to its origin - orbital or nuclear - and to the environment in which it is used.

Electrons in Orbit

In the conditions which obtain at the earth's surface nearly all atoms carry sufficient orbital electrons of their own, or shared with other atoms, to balance the positive charge due to the protons on their nuclei. All chemical properties and changes depend upon the numbers and arrangement of electrons in their orbits, and the formation or breakage of the chemical links between atoms involve the redistribution of these orbital electrons. The formulation and development of the ionic theory and the electronic theory of valency, and concepts such as free radicals and electron density, have brought about a far clearer understanding of the nature of chemical structure and change than had previously been possible. With this understanding have come many of the major advances in chemical research and technology, ranging from commercial developments in the electro-chemical and plastics industries to the spectacular rise of the whole new science of molecular biology.

Electrons in Conducting Solids

Current electricity was already being used commercially on the grand scale well before Thomson's discovery of the electron; nevertheless its visualisation as a shunting movement of loosely bound electrons in a conductor has helped considerably in the theoretical and practical development of current electricity and electro-magnetism. The discovery and development of super-conductivity is perhaps the most promising outcome in recent years of this concept of the electric current.

Electrons in Semi-conducting Solids

Certain substances or assemblies allow the passage of electrons in one direction more readily than in another. These include particularly some of the elements (and their compounds) whose orbital electron structures put them in the middle groups of the periodic table - between the obviously metallic and the obviously non-metallic elements. If the regular crystal structure of one of these materials is thrown out of step, as it were, by the introduction of "impurity" atoms, and if another material is placed in contact with it, electrons will flow across the boundary more readily in one direction than in the other. Such devices form the basis of solid-state diodes or rectifiers which are used both in low-current electronic devices (of which the crystal and cat's whisker was an early example) and, increasingly, for handling large amounts of electricity in a.c./d.c. power rectifiers. The transistor is another solid-state semi-conductor device in which an applied potential difference is used to control the size and direction of the current; it can act as a rectifier, an amplifier or a switch without moving parts. These devices are the basic components upon which modern high speed computers are entirely dependent; they are used increasingly in all kinds of other electronic systems from domestic portable radios to advanced navigational guidance systems.

Free Electrons in Gases and Plasmas

If sufficient energy is transferred to the atoms of a gas to ionise them (that is, to shake free some of the outermost electrons from their orbits) the gas will become a conductor of electricity and is called a "plasma". Gases, especially at low pressure, can be ionised by heat, by X-rays, by the electro-magnetic or corpuscular radiation from radioactive decay, by high-frequency alternating current fields or by sufficiently high direct current potential differences. When a current flows in a plasma some of the atoms are excited even further and electrons are pushed into abnormal orbits from which they revert with the emission of light or other electro-magnetic radiation of characteristic frequency. This way of producing light first became familiar in "neon" signs and is now very widely used in the form of fluorescent lighting, in mercury or sodium street lamps, in ultra-violet lights and in electronic flash tubes. The earliest commercial form of electric light- the carbon arc lamp - relies upon a plasma initially created by the intense heat of an electrical short circuit and sustained by the heating effect of the current continuing to pass through the plasma. Arc lighting is still used in cinema projectors and searchlights, but the major use of the electric arc is now in welding, either in air or in an inert gas such as argon, usually at atmospheric pressure. The mercury arc is still the most important type of a.c/d.c. power rectifier.

The plasma which carries the current in an electric spark is produced by the break-down of the insulating properties of the intervening gas - i.e., its ionisation - by the potential difference across it. Intense local heating is produced in the path of the spark. The most familiar application is in the sparking plugs of the internal combustion engine, and other uses include the firing of explosive charges and the spark erosion machining of complex shapes; spark-gaps are used in the safeguarding of electrical equipment, and in the operation of some types of radio transmitter.

Electrons in Vacuo

Electrons "boiled off" from a hot cathode will carry a current to an anode held at a positive potential. This forms the basis of the diode valve which, by allowing a current to flow in one direction only, acts as a rectifier. With the addition between the cathode and the anode of a grid on which the potential can be varied at will to control the flow of electrons from cathode to anode, the valve can be used as an amplifier. These simple valves and developments from them - some extremely complex - form the basis of nearly all radio, radar and television transmission systems and of most receivers, as well as of many industrial instruments.

In the cathode ray tube familiar to television viewers a focused beam of electrons from a hot cathode is controlled in intensity by the incoming signal, while it is made to scan a fluorescent screen in step with the transmitter; the visible image that is produced corresponds to that "seen" by the television camera. Radar receivers and many kinds of industrial instrument also use cathode ray tubes to produce visible signals convenient to interpret or record. Scanning beams of electrons are also used in T.V. camera tubes; in one type the electron beam scans a light-sensitive plate on to the other side of which the picture is optically focused; electrons are re-emitted in accordance with the brightness of the optical image at each point of the scan, and these provide the signals which are amplified and transmitted to the receiving station.

X-rays are produced when a beam of electrons from a hot cathode excites the orbital electrons in the atoms of the target anode; the energy of the X-rays depends upon the atomic number of the target material and upon the energy of the electrons.

For most practical purposes, including medical diagnosis and therapy and industrial non-destructive testing, the target is a heavy metal such as tungsten; the electrons are given an energy ranging from 1 to 1,000 kilovolts, either by applying a simple potential difference between the cathode and the target anode or (for the highest energies) by employing some form of additional acceleration such as a linear accelerator or a betatron.

A beam of electrons in vacuo is used in the electron microscope; the beam passes through the specimen and is focused by means of a compound system of electromagnetic lenses (analogous to the optical lenses in a conventional microscope) upon a fluorescent screen; here it can be examined optically or recorded photographically. In a more recent version the electron beam scans the target in a manner similar to that in a television camera (see above) and the emitted electrons provide a current which is amplified and forms an image on a cathode ray tube screen. Magnifications of several hundred thousand times are obtainable with the electron microscope.

Beams of electrons in vacuo or emerging into air from a vacuum tube can deposit a great deal of energy in a short time. These are finding increasing applications in industry; for example, their heating effect is used for the welding of particularly difficult materials, while their ability to promote certain chemical reactions before causing a significant rise in temperature is used for cross-linking polyethylene to raise its melting point or to give it the property of heat-shrinkability. Electron beams are being tried experimentally for the ultra-rapid drying of industrial paints, particularly on surfaces which cannot be heated without damage, and their biological effect enables them to be used for cold-sterilising surgical materials or articles where no great degree of penetration is required, or where the dose rate has to be higher than that which can be achieved by γ-ray treatment.

Beta-particles - Electrons from Atomic Nuclei

When a radioactive atom undergoes β-decay a neutron changes into a proton and an electron, the latter being flung out from the nucleus with an energy characteristic of the particular radioisotope; in the case of many of these isotopes one or more γ-ray photons are also emitted. Beta particles have found many practical uses, particularly in industrial measurement and control devices where the extent of their absorption or scattering by the material under test is measured electronically; a signal is produced which can be made to indicate the thickness, density or mass per unit area of the material; where low energy β-particles are involved the scattering is to some extent dependent upon the atomic number of the material. The signal can be fed into a metering or recording device, or back into the system which controls the characteristic being measured. Applications range from the laboratory measurement of the thickness of the gold conducting layer on a printed circuit to the automatic control of an entire sheet-metal rolling-mill.

Like cathodic electrons, beta-particles can be used to excite X-rays from other atoms; these isotope-produced X-rays are used in industrial devices, particularly for non-destructive analysis of alloys and minerals in factory or field, and for the continuous monitoring of the sulphur content of hydrocarbon oils.

Because of the ease with which β-particles can be detected, β-emitting radioisotopes are used as tracers in a very wide range of research, especially in biochemistry, medical diagnosis and industrial process investigations.

Because of their ionising properties, beta-particles are used for medical treatment where limited penetration is required; for example, strontium-90 in specially shaped applicators is used for the treatment of the cornea of the eye.

Tritium and Strontium

Because of its low radio-toxicity, long halving-time and relative cheapness, tritium (hydrogen-3) is used as an activator in luminous signs, for which it has largely replaced radium and strontium-90. This last, however, being available in large quantities from spent nuclear fuel and having a halving-time of 28 years, is finding application in the powering of thermo-electric devices such as flashing navigational beacons; once installed these can be expected to go on working for a decade or more without attention.

POSITRONS

Radioisotopes that are rich in protons, as opposed to the more plentiful and easily produced isotopes rich in neutrons, decay by emitting positrons (positive electrons). When a positron comes to rest in matter it reacts with an ordinary (negative) electron and the whole rest mass of the two particles is converted into two photons of 0.51 MeV electro-magnetic radiation, which can be very readily detected by a scintillation counter. If two such counters, arranged to register only when both receive a signal at the same time, are set up on opposite sides of a source of positrons the annihilation photons will be detected unmistakably even against a background of other radiations. A positron emitter can in this way be located and its strength measured, even at very low concentrations and through a substantial bulk of surrounding material, more or less independently of the background radiation. A typical example is the use of cyclotron-produced oxygen-15 for the study of the heart-lung function; here the uptake of oxygen into the lungs, its progressive removal by the blood circulation and its final exhalation, can be studied in detail in different regions of each lung by external counting of the annihilation radiation.

NEGATIVE π-MESONS

Although work is still at the early experimental stage it is possible that beams of negative π-mesons may one day prove to be valuable weapons in the fight against cancer. Unlike γ or X-rays they can be made to deposit the bulk of their energy at a controlled depth and in a limited volume of tissue. The biological effect of a negative π-meson beam at the tumour depth will be produced mainly by alpha-particles that result from nuclear interactions of the π-mesons when they come to rest. Such alpha-particles have a high relative biological efficiency and a low oxygen enhancement ratio - that is to say, they do not need oxygen to be effective. In all other regions radiation is produced by lightly ionising particles which will have a low relative biological efficiency. At the present time potentially useful beams of π-mesons can only be produced in a few of the world's largest particle accelerators. For further information on this development see the 1964 Rutherford Memorial Lecture by Professor P. H. Fowler, F.R.S., of Bristol University (Proc. Phys. Soc., June, 1965, pp. 1051-1066).

PROTONS

Since hydrogen atoms consist of single protons each with one orbital electron, positively-charged H^+ ions are in fact free protons (unless combined for example, as H_3O^+ in aqueous solution). Many chemical changes in which hydrogen takes part involve the existence - albeit fleeting - of free protons; in certain branches of organic chemistry the intra- or inter-molecular migration of protons plays an important part.

Free protons are present in the partially ionised gas of the "atomic hydrogen" welding torch whose heating power derives largely from the catalytic re-formation at the metal surface of H_2 molecules previously dissociated by passage through an electric arc.

Beams of protons produced by accelerating hydrogen ions in a cyclotron are used in the production of proton-rich radioisotopes which decay by positron (β^+) emission.

Protons ejected from a linear accelerator may one day find application as plasma jets for the propulsion of space vehicles.

NEUTRONS

Since the discovery in 1938 of nuclear fission, neutrons have played a role of rapidly increasing practical importance.

When a neutron causes fission of the nucleus of a uranium-235 or plutonium-239 atom, two or three fresh neutrons are produced in the process; this can lead in certain circumstances to a self-propagating chain reaction which can either be kept going at a steady rate in a nuclear reactor or made to build up explosively in a bomb. The energy produced is of the order of 10 million times that produced in chemical reactions involving the same mass of material.

NUCLEAR WEAPONS

If a mass of fissile material is assembled of such a size and shape that the rate of neutron production by fission exceeds the rate of neutron loss from the surface or by other wastage, and if the material can be kept together for long enough for a substantial proportion of the fissile atoms to react, a nuclear explosion will result. The temperature - tens of millions of degrees C. - attained in an "atomic" bomb of this type is sufficient to bring about the fusion, in a thermonuclear or "hydrogen" bomb, of light nuclei with the production of an even more violent explosion.

NUCLEAR POWER REACTORS

If the nuclear chain reaction is sustained at a steady level in a nuclear reactor by ensuring that just one neutron from each fission goes on to cause one further fission, the energy produced can be used to raise steam and generate electricity. About 14 per cent. of Britain's electricity is at present being generated in nuclear power stations, and by the 1970s nuclear generation is expected to be the cheapest way of making electricity in this country.

RADIOISOTOPE PRODUCTION

The hailstorm of neutrons present in an operating nuclear reactor can be used to make materials or objects radioactive by introducing further neutrons into their nuclei; such neutron-rich nuclei will decay by the emission of β-particles with, in some instances, γ-rays as well. Radioactive isotopes, both proton-rich and neutron-rich, are also produced directly in the fission of uranium or plutonium; these fission products can be separated chemically from the bulk of the spent fuel and converted to the required chemical or physical form. Radioactive isotopes of almost every element are now available commercially. The fissile isotope plutonium-239 is produced by bombarding uranium-238 with neutrons arising from fission of uranium-235 or of plutonium-239.

ANALYSIS WITH NEUTRONS

Specimens or materials for analysis may be bombarded with neutrons and the radiations subsequently given off by the radioisotopes so formed may be examined; the nature of these radiations indicates which radioisotopes are present, and their intensities indicate the amount of each. Knowledge of the nuclear reactions leading to the production of these radioisotopes makes it possible to determine, quantitatively and qualitatively, many of the elements constituting the original specimens. This technique, known as activation analysis, is limited in its practical application to elements which readily absorb neutrons. Because of its extreme sensitivity, it is particularly valuable in trace analysis, for example in forensic work; it can also be adapted to certain types of routine non-destructive analysis in industry, e.g., oxygen in steel. The usual source of neutrons for activation analysis is a nuclear reactor, but in the case of oxygen in steel and other on-the-spot analyses where no reactor is available increasing use is being made of neutron generators; in these, 14 MeV neutrons are produced by reaction between electrically accelerated deuterium (hydrogen-2) ions and a tritium target, according to the equation

$$^{3}_{1}H + ^{2}_{1}d \longrightarrow ^{4}_{2}He + ^{1}_{0}n + 17{\cdot}6\ MeV.$$

Portable instruments for use on site, e.g., for bore-hole logging or for soil-moisture measurement, depend upon neutrons produced on the spot by nuclear reactions such as that between beryllium and α-particles from radioactive decay; the instruments usually detect either prompt γ-rays (e.g., from chlorine in the brine associated with oil-bearing formations) or thermalised (slow) neutrons, scattered back by the hydrogen nuclei of water molecules, for example, in the soil adjacent to the neutron source.

Other neutron techniques under development include quantitative measurement by activation analysis of constituents of the living body (e.g., total sodium or chlorine); neutron-beam therapy including that in which implanted materials such as boron are activated in situ; and industrial neutron radiography, which can reveal small inclusions of light materials that absorb or scatter neutrons, in a mass of much heavier material that is relatively transparent to neutrons but is too dense or massive to be examined satisfactorily by X-rays or γ-rays - for example, a piece of organic matter embedded in a block of lead.

MU-MESONS

An interesting project involving the use of yet another elementary particle - the mu-meson - has been announced since this article was originally prepared (see "New Scientist", 23rd June, 1966). This is a joint U.S.A. and United Arab Republic proposal to examine the transmission of cosmic-ray mu-mesons through one of the Pyramids, in an effort to detect and locate any hitherto undiscovered burial chambers.

NEUTRINOS

Finally, even the elusive neutrino may prove useful, if only to scientists: an attempt is being made to use neutrino flux measurements, made deep underground, to study the nuclear reactions taking place in the heart of the Sun ("New Scientist", 10th November, 1966).