Alpha – Beta – Gamma: A Short Introduction to Radioactivity

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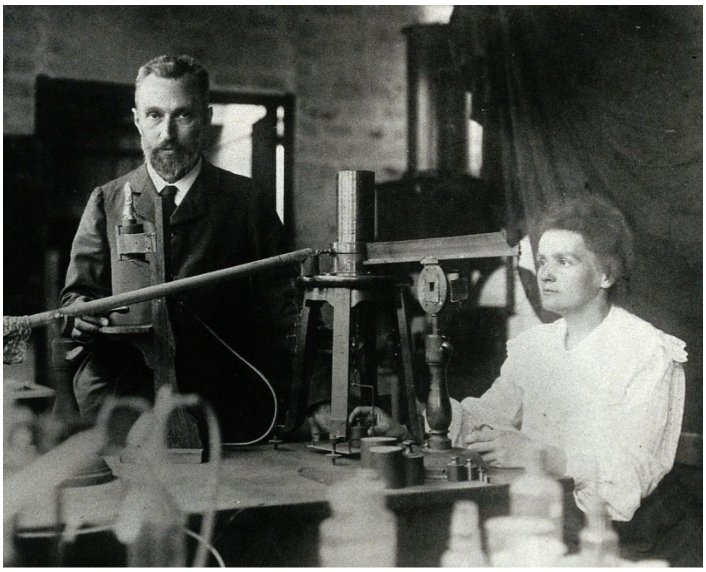
(based on the President's Lecture of 25 January 2016)

Introduction

Radioactivity is a highly emotive subject, a source of great wonderment, though feared by many. It is responsible for dramatic advances in energy generation, medicine and industry, yet at the same time it is associated with accidents in the peaceful uses of radioactivity, and alas, with destruction from nuclear explosions. However, these are extreme examples of a process which has been going on around us since the dawn of the earth. Radioactive material was present in the form of unstable atoms when the earth was formed 4500 million years ago. This has been decaying slowly ever since and small amounts remain. The result is that some radioactivity is present in virtually all materials -- in the soil, in our building materials and even in our food and our own bodies. Perhaps it is surprising, then, that radioactivity has been known to man for little more than 120 years.

Discovery and Early Development

In 1896 the French engineer and scientist, Antoine Henri Becquerel, was experimenting with phosphorescent uranium salts and found that they fogged photographic plates in a similar way to X-rays, which had been discovered by Röntgen the previous year. Becquerel's interest was taken up by two workers in his laboratory, Marie and Pierre Curie, who through experiments with the uranium-bearing material pitchblende, discovered two further elements emitting radiation, polonium and radium. The Curies coined the term "radioactivity, and very soon discovered the property of radium to destroy tumour cells in the body.



Pierre and Marie Curie in their laboratory (Internet Image)

The next great figure in the story of radioactivity was the New Zealand-born physicist, Ernest Rutherford. He discovered that the atom, previously thought to the smallest indivisible particle of matter, consisted of a charged nucleus surrounded by electrons, and that radioactive decay results in the disintegration of atoms into smaller atoms with the emission of radiation. He observed that there were different types of radiation with different penetrating powers, and these he classified as alpha particles, which are helium nuclei and the least penetrating, beta particles which are electrons, and gamma rays, the most penetrating. Rutherford also identified the important property of half-life, a unique characteristic of each radioactive element which ranges from a fraction of a second to millions of years.

Hazards and Precautions

The discovery that radiation could destroy tumours, and the property of X-rays to reveal internal features of the body, led to rapid development of therapeutic and diagnostic procedures in the years leading up to and during the 1914 – 1918 war. It was not long, however, before it was realized that radiation caused tissue damage among experimenters and practitioners. Thus precautions were developed at an early stage, and these were based on three principal elements, namely to keep exposure as short as possible, to keep the source of radiation away from the body, and to place a layer of shielding material between the source and the body. These basic elements of protection, time, distance and shielding, remain the basis of radiation protection to the present day. The need for radiological protection became widely recognized in the 1920s, and a number of international conferences were held to establish agreed principles of measurement and regulation. Units were established to measure quantities of radioactivity and dose absorption, the most common units used today being the becquerel (which is one disintegration per second), and the sievert (or more often the millisievert) respectively.

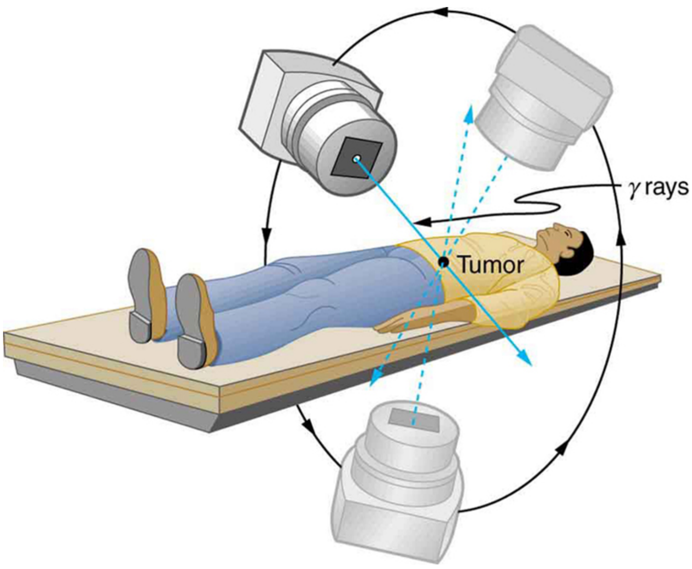
The principles of measurement and protection enabled recommendations to be developed for limitation of dose rates, protection against radiation damage, and the handling and disposal of radioactive materials. These principles continue to be developed and maintained by the International Commission on Radiological Protection.

Applications of Radioactivity

Radioactive materials are generally useful either for the energy they produce, or for the ease with which the ionizing radiation can be detected, so that they can be used for measurement or as tracers. Applications are thus wide-ranging and include medicine, industry, power generation, archaeology, consumer products and, sadly, warfare.

Medical Uses

Radioactivity found early application in medicine, and its power to destroy tumours remains central to the treatment of cancers today. It is most important to direct the radiation to the site of the tumour whilst limiting its effect elsewhere, and this is achieved by the technique of teletherapy, whereby the source irradiates the tumour from outside the body. A powerful gamma radiation source, typically cobalt-60 (half-life 5.27 years), is mounted in a rotating head so that as it rotates it strikes the tumour continuously, whilst impacting the surrounding tissue fleetingly. An alternative approach for the treatment of brain tumours is to mount an array of sources in a helmet, each positioned so as to target the tumour from a different position. A tumour may also be treated by a technique known as brachytherapy, using radiation from shorter half-life sources, e.g palladium-103 (17 days), or caesium-131 (9.7 days), placed inside the body, either permanently or temporarily.



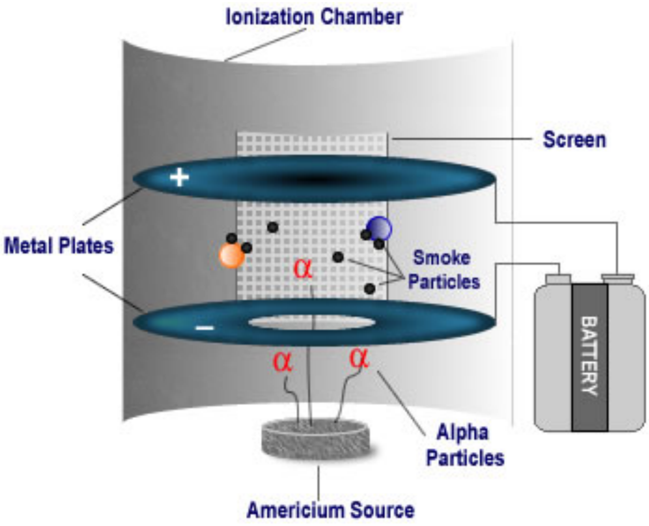
The Principle of Teletherapy (Internet image)

The ability to detect radiation is widely used in medicine for diagnostic investigations. X-rays are the best known diagnostic radiation tool, but radioactive chemicals introduced into the body are used to track the flow of fluids and indicate abnormalities in the functioning of many organs including the brain, heart, thyroid, lungs, liver, gall bladder, kidneys, the skeleton, and the blood, and to track the progress of tumours. One of the most commonly used tracers nowadays is technetium-99m with a half-life of 6 hours. It is a metastable isotope which results from the radioactive decay of molybdenum-99, and itself decays to the comparatively stable technetium-99 (212,000 years). The short half-life of Tc-99m means that it can be used in the body and does not linger, but it cannot be stored and has to be generated at the time of use. A technetium generator employs Mo-99 which decays to form Tc-99m which is chemically extracted and applied to the patient.

<u>Industrial and Technical Uses</u>

If medical diagnosis and treatment was the first application of radioactivity, this has been followed over the years by numerous applications for the benefit of safety and efficiency in industry, research and technology, agriculture, and in our homes.

We are all familiar with domestic smoke detectors, and one of the common types, the ionizing smoke detector, is based on the radioactive isotope americium-241 (half-life 432 years) which emits alpha particles to activate an ionization chamber. When smoke enters the chamber, the alpha particles are absorbed causing a change in the conductivity of the air, which then triggers the alarm to sound.



A Diagram of an Ionizing Smoke Detector (Internet image)

The sterilizing properties of ionizing radiation are well-known, and the penetrating power of gamma radiation makes it a favoured medium for the sterilization of many items including medical devices, biological samples and food. Radiation sterilization is often considered more thorough than other methods such as heat treatment, and has the advantage that it can be applied after packaging. The gamma emitters cobalt-60 and caesium-137 are widely used. Food irradiation is highly effective for maintaining “freshness”, but is controversial on grounds of possible reduction of quality and long-term health effects.

Industrial applications of radioactivity include thickness gauging in metal sheet manufacture, oil well logging, and gamma radiography. The last of these is a powerful technique for the detection of flaws in manufactured products and in industrial plant in service, including pipelines, generating installations and chemical plant. The technique is similar to X-ray examination, where the radiation penetrates the item to be examined and forms a picture on a photographic film or electronic sensor.

Luminous dials on watches and military instruments were very common in the twentieth century. The luminous effect (radioluminescense) is caused by the excitation of atoms by radiation particles, typically beta particles. ***Radium*** was a major source for luminous dials, being mixed in a paint with a phosphor (typically zinc sulphide) which emits light under the energy of the decaying radium. Radium (half-life 1600 yrs) is a significant gamma emitter, causing extensive damage to workers and exposure to users, hence it was eventually discontinued. Tritium (half-life 12.3 years) is considered a safer source of radiation as it emits a very low energy beta radiation, and is virtually the only radioactive material used for this purpose now. It is enclosed in a borosilicate glass tube coated with a phosphor to form a continuous light source.

One of the more fascinating applications of radioactivity is radiocarbon dating, which is a great boon to researchers and archaeologists seeking to ascertain the age of historic artefacts. Carbon dioxide in the atmosphere contains a certain proportion of the radioactive isotope carbon-14, and this is fixed in plant and animal tissue,. This decays over time, hence measurement of the ratio of carbon-14 to the stable carbon-12 provides an indication of the age of the article under investigation. A notable application is the dating of the Turin Shroud, and a further recent example is the examination of an early manuscript of the Qur'an, revealing its origins from about the time the Prophet Muhammad is believed to have lived.

The Turin Shroud (Internet image)

All the above applications use relatively small amounts of radioactive material, and depend on the properties of radioactive material to decay naturally, yielding different types of radiation which can be used either for the energy they impart or for their ability to be detected for the purpose of tracing or measurement.

Nuclear energy is in a different league. It uses very large amounts of radioactive material, and the energy is derived from nuclear fission, whereby the energy within the atom is released by the break-up of the atom under bombardment by neutrons. The technology is based upon the fissile isotope of uranium, U-235, which when struck by neutrons breaks down into smaller atoms releasing energy and further neutrons, establishing a chain reaction and a continuous release of energy which is used to generate steam to drive a turbine generator.

Two Nuclear Power Stations: Oldbury on Severn, Magnox (left), Sizewell B , PWR (right) (Internet images)

The use of nuclear power for electricity production was pioneered in the United Kingdom in the 1950s, and the early installations (the Magnox power stations) used natural uranium fuel with the heat extracted by carbon dioxide gas. This principle was developed into a more powerful gas-cooled reactor using enriched uranium fuel (the Advanced Gas-Cooled Reactor), and the most recent installation uses enriched fuel with water cooling (the Pressurized Water Reactor, PWR). Nuclear power forms about 18% of electricity generation in the UK, and despite some disadvantages including the possibility of accidents and the disposal of the waste products, it is a stable non-carbon-emitting source of energy

Summary and Conclusion

This brief article has reviewed the origins and discovery of radioactivity, the works of the early pioneers, Bequerel, the Curies and Rutherford, and has discussed some of the hazards and precautions associated with the handling of radioactive materials, leading to the development of modern regulations and procedures to ensure safety. Some of the many uses of radioactivity have been explored including medical techniques to promote health, industrial applications to improve efficiency and safety, and scientific techniques to aid research, concluding with the major use of radioactive material to generate electricity in nuclear power stations.