Radioactivity Fundamentals

An Online Continuing Education Course for Engineers

Course Number: R-3012

Credit: 3 Hours / 3 PDH / 3 CPD

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Introduction:

With the increased interest in the application of nuclear power in electric power generation and the associated engineering, a review of the principles of radioactivity is important. There have been changes in the units and measurement of radioactivity in the past 30 years. This course is intended to be a review of the fundamentals of radioactivity; what it is, where it is found, what its characteristics are, how it is measured, and what its effects and its uses are. For those needing to go deeper into aspects of radioactivity, the course will serve as an introduction to such topics as calculations of decay constants & half-lives and health physics.

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Definitions:

The following definitions are important in understanding the material presented in this course.

1. Created nuclides - those that do not (or no longer) exist in nature, but have been brought into being by bombardment of atoms with particles from a radioactive decay or from accelerators or by fission in nuclear reactors.

2. Fission - splitting of a heavy atomic nucleus into two or more parts (two being most common) of intermediate atomic weight.

3. Ionization - a process in which one or more electrons are liberated from a parent atom or molecule or other bound state.

4. Isobars - nuclides which are chemically different, but have the same mass number.

5. Isomers - pairs of nuclei which have the same atomic number and mass but have different radioactive properties - one with a measurable half-life decaying to the other which is stable.

6. Isotopes - nuclides chemically identical, having the same atomic number but differing in atomic mass. An element in its natural state frequently consists of two or more isotopes.

7. Nucleons - fundamental particles which make up atoms; usually referring to protons and neutrons.

8. Nuclide - a species of atom characterized by the constitution of its nucleus, i.e. by the number of protons and neutrons it contains.

9. Radioactive decay – change in a nuclide by the emission of particles or energy or both to become a different nuclide.

10. Spontaneous decay – a process by which a nuclide undergoes radioactive decay without external influence.

11. Spontaneous fission - a process in which a heavy nuclide undergoes division in the ground state without bombardment of particles or the addition of energy from the outside.

Radioactivity

WHAT IS IT?

As considered here, radiation may be thought of as the process of transmission of energy by means of electromagnetic waves or particles. This radiation may be further categorized as ionizing or non-ionizing where ionizing refers to the production of ionized particles by the incident radiation. In this respect solar radiation is non-ionizing although it is energy transfer by electromagnetic waves.

Ionization by electromagnetic radiation requires that the incident radiation have a minimum amount of energy to cause particles to be ejected from a nucleus and solar radiation does not have the necessary energy content. On the other hand, some of the naturally occurring elements have a characteristic which causes them to eject (at the rates particular to these elements) particles with sufficient energy to produce ions in substances which they contact. It is this ionizing radiation that will be of concern in this course. Ionization is produced by particles or photons. An understanding of this process begins with a review of atomic historical developments.

HISTORICAL HIGHLIGHTS:

Ionizing radiation comes primarily from cosmic rays, natural elements, and created radioactive nuclides. Although natural radioactive elements have existed since the Earth was formed, recognition of atoms and atomic behavior had to be developed. While the understanding and use of radioactivity and atomic energy are recent developments, the idea of an “atom” as an elemental entity was held by the ancient Greeks. When interest in fundamental building blocks for material began anew in the 17^{th} century, the concept of atoms was picked up and explored.

The earliest efforts to develop these concepts were made to support chemistry. By the beginning of the 19th century, the four laws of chemical combination had been developed. These were the laws of: Conservation of Mass, Definite Proportions, Multiple Proportions, and Reciprocal Proportions. These laws together with the evidence of specific combining weights had been developed on the bases of experiments. Their consistency and uniformity called for an explanation.

Early in the 19th century (1803) Dalton proposed an atomic hypothesis to account for the facts shown by the laws of chemical combination. Dalton's proposal postulated that (1) chemical elements consist of discrete particles of matter, atoms, which cannot be subdivided by any chemical means and which remain individual in chemical changes (2) all atoms of each element are identical in all respects. The atoms of different elements differ in weight so that each element is characterized by the weight or mass of its atoms. (3) chemical compounds are formed by the union of atoms of different elements in simple numerical proportions. While this proposal satisfied some of the laws, it had deficiencies --- such as regarding water as the combination of one atom of hydrogen and one atom of oxygen.

Although Dalton's hypothesis was simple and met some of the experimentally determined laws of chemical combination, it did not agree with the findings (1805-08) of Guy-Lussac on chemical combinations of gases. Avagadro showed that, if the basic particles of gases were aggregates of a number of atoms (which he called molecules), and equal volumes of all gases under the same conditions contained the same number of molecules, the disagreements between combining volumes of gases and the atomic hypothesis could be resolved.

To further the atomic hypothesis it was necessary, for practical reasons, to establish a standard for atomic weight. Oxygen, with an atomic weight of 16 and a molecular weight of 32, was chosen because oxygen combines with nearly all elements to form stable compounds. Also the choice of 16 for the atomic weight of oxygen meant that the atomic weight of hydrogen would be nearly 1 and that no element's atomic weight would be less than one.

With a standard for atomic and molecular weights established, it was possible to calculate the volume of a gram-molecular weight of a gas at standard temperature and pressure (S.T.P.). Experiments with many gases confirmed that this volume is 22.4 L. The number of molecules in any gas in 22.4 L at S.T.P as well as the number of atoms in a gram-atomic weight of any element have been shown to be the same. This number is called the Avogadro number or Avogadro constant and its value (currently accepted) is 6.0221367×10^{23}.

The chemical and physical properties of the elements continued to be discovered and collected. It was noted that there were similarities in properties and characteristics. Categorizing the elements according to similarities seemed to be a logical step. Mendelief, in 1869, proposed his Periodic Law. Arrangements of elements according to this Law were based on atomic weights. This arrangement enabled prediction of other elements that might be found and set steps in place for further advance in atomic theory.

In his work on the electrolysis of aqueous solutions of chemical compounds, Faraday found chemical relations that suggested specific changes were transferred by atoms or groups of atoms which he called ions. In 1874 Stoney postulated that there was a natural unit of electricity and suggested the name electron for this quantity. Faraday's experiments enabled the calculation of the ratio of the ionic charge to the mass of the atom with which it was associated in a given solution.

Roentgen, in 1895, discovered x-rays which provided a convenient means to ionize gases. These ionized gases conducted electricity. Experiments with conductors sealed in a glass tube containing a gas at low pressure, showed that the rays traveled from cathode to anode – these rays were called cathode rays. It was found that these cathode rays; could penetrate small thicknesses of matter, carry a negative charge, are deflected by electric or magnetic fields, and carry a considerable amount of kinetic energy. Thompson's experiments in 1887 led to the conclusion that the charge on the electron is the same as that on the hydrogen atom and the mass of the electron is 1/1800 of the hydrogen atom.

Meanwhile, in 1896, Becquerel had discovered that crystals of a uranium salt emitted rays which were similar to x-rays. The Curies followed, in 1898, with the discovery of two other elements which emitted rays -- polonium and radium. The existence of the electron, the discovery of x-rays, and the emission of charged particles by some elements provided bases for the study of the atomic structure.

On the bases of the theories and experimental evidence developed in the 19th century, attempts were made to describe atoms and atomic nuclei. Classical physics of the time was not adequate. Planck introduced the quantum theory of heat radiation in 1901. This very satisfactorily explained the dependence of the intensity of blackbody radiation upon the frequency of the radiation. The theory predicted that a physical system capable of emitting electromagnetic radiation can vary only in discrete levels or quanta. This theory could explain not only thermal radiation, but also other problems such as the photoelectric effect; the emission of charged particles from a metallic surface when light of a frequency greater than a critical value falls on the surface. In 1905, Einstein worked out a photoelectric law based on Planck's idea of quanta of energy. Millikan's experiments in 1916 confirmed the validity of Planck's hypotheses and Einstein's deductions.

In 1905, Einstein had developed the Special Theory of Relativity. An important result of this theory was that it confirmed the validity of the Lorenz transformation which showed that space and time are not independent quantities but are related and that the mass of a body increases with its velocity as postulated by Fitzgerald. Results obtained from experiments using high-velocity particles from a radioactive decay showed the mass does increase with velocity; the increase becomes significant when the particle’s velocity becomes greater than 10% of the speed of light.

The variation in mass with velocity introduced changes in the calculation of the energy of a particle. These new calculations showed that the change in kinetic energy is proportional to the change in mass and the proportionality factor is the speed of light squared. This indicated that a large amount of energy could be obtained from the conversion of a small amount of mass. For instance, 1 gram of mass would convert to 8.99×10^{10} kilojoules (8.5×10^{10} BTU). The prospect of obtaining such a quantity of energy was very enticing, but obtaining it required access to the atomic nucleus.

In 1908, Geiger proposed and developed (for Rutherford) a crude instrument that could measure radioactive emissions. This was a great improvement over visually observing and counting flashes from these events that occurred in phosphor on a plate. Geiger’s instrument was improved and is still used today as a Geiger counter.

Early in the 20th century, the study of radioactive materials led to the discovery of isotopes. Experimental work on isotopes showed that the lightest charged particle emitted from a nucleus had the same mass as a hydrogen nucleus. This particle was given the name proton representing its importance as a fundamental building block or nucleon.

To account for the difference between charges in an atom and its weight (of atoms heavier than hydrogen), it was initially thought that there were some electrons in the nucleus. Experimental evidence showed that this was not the case and in 1932 Chadwick demonstrated the existence of a neutral particle, the neutron, which had been postulated by Rutherford in 1920. The existence of protons and neutrons enabled Heisenberg to develop, in 1932, a detailed theory of the atomic nucleus. In this concept, the total number of protons and neutrons in the nucleus is equal to its mass number A., the number of protons is indicated by the atomic number Z, and the number of neutrons is A - Z. More experimentation with and investigation of atomic characteristics led to the finding of other properties such as the attractive and repulsive forces, magnetic and electric properties, spin (angular momentum), statistical nature, and parity. Neutrons, without electric charge, made more penetrating missiles for further experimentation.

The Joliot-Curies (Frederick and Irene) took up the experimentation to confirm the existence of positrons (discovered by Anderson in 1932) and to look for evidence of neutrons. In the course of bombardment by alpha particles to produce neutrons, they found out how to make created radioactive nuclides. This result, reported in 15 January 1934, provided the first proof of artificial transmutation. Joliot, in his part of a joint Nobel Prize address, mentioned the possibility of transmutation of an explosive nature. Szilard, when he heard of the Joliot-Curie's discovery, saw the possibility of a chain reaction, already known in chemistry, in the nuclear sense. Szilard also realized that neutrons would be more effective than alpha particles in producing transmutations, but he did not have resources that would enable him to investigate. Fermi, in Rome, did. Fermi had assembled a well-equipped laboratory and a capable staff. He prepared materials that produced neutrons for bombardment and proceeded to investigate the effect of neutron bombardment on all the [then known] elements. Some of the findings suggested that bombardment of uranium produced an ele... ...bove atomic number 92; the naturally occurring element with the hi... ...This was startling news and others attempted to d... ...e's found what seemed to be ele... ...n and Strassmann did also. Finally in 1... ...a uranium nucleus, having absorbed ... ...more) nuclides of much lower atomi... ...was called fission after the biologica...

Szilard and Oppen... ...nergy releases. But now the political sit... ...azi advances in countries in Easterr... ...d caused many scientists to move t... ...me to the US. There was, in the U... ...uclear energy to make high-power ex... ...be to find a nuclide which fission... ...f fissioning, released more neutr... ...d to take care of any losses of neutror... ...$_2U^{235}$ when fissioned, produced s... ...ner urged secrecy and recomm... ...was made with the U.S. Navy. The N... ...ments were made to deliver a report on the ... a letter of recommendation for action by Einstein to F... ...velt. The President decided that this matter required action and directed the formation of a committee. The effort then grew rapidly into the Manhattan Project, with its laboratories, factories, workers, and secrets. Large-scale production of created radionuclides was achieved with a successful operation of the first nuclear reactor (CP-1) in December 1942 and the many reactors to follow.

SOURCES of RADIOACTIVITY

Earth's Crust

As seen from the historical highlights, early researchers found materials that, because of emitted particles and rays, exhibited unusual behavior and produced strange effects. This characteristic they called radioactivity. Most of this material came from the ore mines in the mountains between Czechoslovakia and Germany. From the pitchblende ore, Klaproth extracted, in 1789, a metal he named uranium. Bequerel found that Uranium was radioactive. Schmidt and Curie independently found that Thorium, which had been identified by Berzelius in 1828, was also radioactive. Near the mines in the