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VCE Physics Unit 1

Area Of Study 1, Nuclear Physics and Radioactivity, Study Notes

Nuclei

The major particles in the nucleus of an atom are called **nucleons**. There are two kinds of nucleons: **protons** and **neutrons**. Protons have a **positive** electrical charge. Neutrons have no electrical charge. Protons and neutrons have similar mass.

The number of protons in a nucleus is called the **atomic number**, is represented by the pronumeral Z and defines the element constituted by the atom.

The total number of protons and neutrons in a nucleus is called the **mass number**, and is represented by the pronumeral A.

$${}_{Z}^{A}X$$

$$A - Z = Number\ of\ neutrons\ in\ nucleus$$

Where: A = Mass number
Z = Atomic number
X = Chemical symbol of element

Isotopes

Separate nuclei may have the same atomic number (the same number of protons), and therefore be of the same element, but may also have different mass numbers, and hence have different numbers of neutrons. Each different possible mass number of a particular element is referred to as an **isotope**. An example is uranium:

${}_{92}^{238}U$ and ${}_{92}^{235}U$ are both isotopes of uranium.

$U238$ and $U235$ or $uranium\text{-}238$ and $uranium\text{-}235$ are alternative methods for notating these uranium isotopes. $U238$ has 92 protons and 146 neutrons, while $U235$ has 92 protons and 143 neutrons.

Some isotopes of elements occur naturally (in the rocks which constitute the Earth), while others are created artificially in nuclear reactors by the absorption of neutrons into nuclei. This process is called **artificial transmutation**. A **radioisotope** is an isotope which is radioactive.

Stability and Instability

Protons, due to their positive charges, electrostatically repel each other very strongly and therefore don't "want" to be in a nucleus together. Neutrons provide a strong **nuclear force**, which acts inwards on a nucleus to overcome the electrostatic repulsion. This nuclear force holds a nucleus together as one object.

A balance between the inwards acting nuclear force of the neutrons and the repulsive electrostatic force of the protons results in a stable nucleus. An imbalance between these forces results in an unstable nucleus, which has a tendency to either break apart (due to too many protons) or collapse in on itself (due to too many neutrons). this is what causes radiation.

Gamma, γ, Radiation

Gamma radiation is a high frequency, short wavelength electromagnetic wave emitted from unstable nuclei due to them "wiggling" about in effort to arrange themselves (and their nucleons) into more stable configurations. Gamma radiation does not consist of particles with mass, and therefore does not result in the decay of nuclei.

Beta, β, Radiation or "Decay"

Beta radiation is the result of a nucleus being unstable due to it having too many neutrons. One of the neutrons "splits" apart to become a proton, an electron and an almost mass-less particle called an *antineutrino*. The new proton remains in the nucleus, adding to the atomic number, while the electron, in this situation referred to as a **beta particle**, is shot out from the nucleus with extremely high velocity, along with the antineutrino.

With the ejection of a beta particle, the mass of a nucleus decays (is reduced) by the mass of an electron and an antineutrino. Some energy is also taken from the nucleus by these particles.

This is nuclear equation for a nucleus that undergoes beta decay:

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}X + {}_{-1}^{0}\beta + \overline{\nu} + E $$

Where: A = Mass number
Z = Atomic number
X = Chemical symbol of element
β = Beta particle
ν = Antineutrino
E = Energy

Alpha, α, Radiation or "Decay"

Alpha radiation is the result of a nucleus being unstable due to it having too many protons. Two protons, along with two neutrons, together as a united entity referred to as an **alpha particle** may be ejected from such a nucleus. The atomic number of the nucleus is therefore reduced by 2, while the mass number is reduced by 4. Having two protons and two neutrons, the alpha particle is identical to an helium nucleus, and takes some of the original nuclei's energy away.

This is the nuclear equation for a nucleus that undergoes alpha decay:

$$ {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}X + {}_{2}^{4}He + E \text{ or} $$

$$ {}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}X + {}_{2}^{4}\alpha + E $$

Where: A = Mass number
Z = Atomic number
X = Chemical symbol of element
α = Alpha particle / Helium nucleus
E = Energy

Relative Properties of the Three Types of Radiation

Type	Speed	Mass	Energy	Penetration Strength	Ionisation Ability
Alpha, α	~0.1c	Heavy	High	Low	High
Beta, β	~0.9c	Light	Medium	Medium	Medium
Gamma, γ	c	Zero	Low	High	Low

Decay Series

A decay series is the sequence of radioactive decays encountered by a nucleus before it becomes completely stable. When a nucleus (referred to as a "parent") of a radioisotope emits an alpha or beta particle, it decays to become the nucleus (referred to as a "daughter") of another element, more stable than the parent, but still radioactive. This radioactive daughter, due to its own instability, then decays (via the emission of an alpha or beta particle) to become the nucleus of yet another element, more stable again but still radioactive. This chain of radioactive decay continues until eventually the nucleus is stable, usually as an isotope of lead.

Beginning from naturally occurring heavy radioisotopes, such as uranium-238, uranium-235, thorium-232 or neptunium-237, a decay series may take millions or billions of years to be complete.

Half-life

Half-life, in seconds, minutes, hours, days or years is the time taken for half of a sample of a particular radioisotope to have undergone radioactive decay. It is therefore a measure of an isotope's radioactivity. Any nucleus in a sample of a particular radioisotope can decay at any moment. Which nucleus decays and when is completely random. The ratio between the quantity of radioisotopes in a sample and the element into which the radioisotope decays can give an indication of the sample's age if the half-life of the radioisotope is known. An example of this is carbon-14, a naturally occurring radioisotope which emits beta radiation to decay into nitrogen-14. Analysing a sample to find the ratio between carbon-14 and nitrogen-14, knowing the half-life of carbon-14 to be 5730 years, enables the sample's age to be calculated.

Half-life can be measured by monitoring a sample's radioactivity over time. Radioactivity can be measured by the number of radioactive decays that occur per unit of time. This is measured in **becquerels**, Bq, and 1 **becquerel** is equal to 1 radioactive decay per second.

Detecting Radiation

There are three devices that are commonly used for the detection of radioactivity.

A **Geiger counter** consists of a sealed tube of argon gas. Inside the tube are electrodes with terminals on the outside of the tube. A small loudspeaker is connected to the terminals. Every time an alpha or beta particle passes into the tube, a gas particle is ionised. This particle it in turn ionises a string of other particles between the electrodes, completing a circuit and sounding as a "click" from the loudspeaker.

A **film badge** can be worn by a person who works with or near dangerous materials to monitor their exposure to radioactivity. It consists of a piece of photographic film sealed from light. Over time the film is affected by radiation. When the film is developed, the image can be analysed to assess the types and quantities of radiation to which the person has been exposed.

A **thermoluminescent dosimeter** can also be worn by a person who works with or near dangerous materials to monitor their exposure to radioactivity. It consists of a piece of lithium fluoride, which reacts to beta and gamma radiation, as well as X-rays and neutrons.

Measuring Radiation

Radiation transfers energy into, and can ionise atoms in, mass to which it is exposed. While the standard unit for energy is the Joule, J, the energy carried by single particles is very low (due to their very small mass), so the unit often used for energy in particle physics is the **electronvolt**, eV.

1eV = the energy gained or lost by an electron as it moves across a potential difference of 1V.
$1\text{eV}=1.6\mathbf{x}10^{-19}\text{J}$, so:

To convert **eV** to **J**, **multiply** by **$1.6\text{x}10^{-19}$**, and
To convert **J** to **eV**, **divide** by **$1.6\text{x}10^{-19}$**.

In the context of organic material, such as the living tissue of a human body, an **absorbed dose** of radiation is measured as an amount of energy transferred per kilogram, in units of **Grays**, Gy.

$$D=\frac{E}{m}$$

Where: D = Absorbed dose, in Jkg^{-1} or Gy (1Jkg^{-1} = 1Gy)
E = Energy transferred into living tissue from radiation, in J
m = mass of living tissue into which energy is absorbed, in kg

Absorbed dose does not consider the type of radiation that has affected the mass to which it was exposed, and different types of radiation have different ionising effects. To take this into account, **dose equivalent** multiplies the absorbed dose by a **quality factor**: 20 for alpha particles, 10 for neutrons (found where nuclear reactions have occurred) and 1 for beta particles, gamma waves and X-rays. The unit for measuring dose equivalent is **Sieverts**, Sv.

$$F=DQ$$

Where: F = Dose equivalent, in Sv
D = Absorbed Dose, in Jkg^{-1} or Gy (1Jkg^{-1} = 1Gy)
Q = Quality factor (no unit)

Dose equivalent does not consider that different organs of the human body vary in their sensitivity to radiation. To take this into account, **effective dose** multiplies the dose equivalent by a weighting for the sensitivity of each organ exposed: 0.20 for the ovaries or testes, 0.12 for the lungs, 0.05 for the liver (as examples). These weightings are then summed together for an overall indication of the extent to radiation has had an affect. The unit for measuring effective dose remains as **Sieverts**, Sv.

$$H=\Sigma(FY)$$

Where: H = Effective dose, in Sv
F = Dose equivalent, in Sv
Y = Weighting (no unit)