20 Nuclear Physics

The Nucleus

Alpha-particle scattering experiment

1. Most scintillations were observed when the detector was aligned along the original path of the α-particles (i.e. undeflected).
   Explanation: Most of the atom is empty space
2. Fewer scintillations were observed at an angle to the direct path on the same side of the gold foil.
   Explanation: The α-particles are repelled by some positively charged object in the gold foil.
3. Rarely, some scintillations were observed on the same side as the α-beam (i.e. deflected by more than 90°).
   Explanation: There must be a very heavy and dense centre core in the atom (later called the nucleus) to be able to reflect the α-particles by such a large angle.

The **unified atomic mass unit, *u*** is $\frac{1}{12}$ the mass of a carbon atom, i.e. 1 u = 1.66×10^{-27} kg (given)

Isotopes

A **nuclide** is an atom species characterized by the nucleon (mass) number A (sum of protons and neutrons) and proton (atomic) number Z (no. of protons). Each nuclide can be described as ${}^{A}_{Z}X$, where X is the symbol for the element. **Isotopes** are different nuclides which have the same proton number but different nucleon numbers.

Mass Defect and Binding Energy

A nucleus is a bound system with lower potential energy than its constituent parts. To disassemble a nucleus, energy is needed.

Mass Defect and Binding Energy

The **binding energy** (BE) of a nucleus is the amount of work needed to take all its constituent nucleons apart so that they are separated at an infinite distance from one another, i.e. nucleus + BE → nucleons

Mass defect

Einstein postulated the **equivalence of mass and energy**, where any change in the energy *E* of a body implies a corresponding change *Δm* in its inertia mass, i.e. $E = \Delta mc^2$
Σ(masses of constituent nucleons) > mass of nucleus, and 1 MeV = 1.60×10^{-13} J.

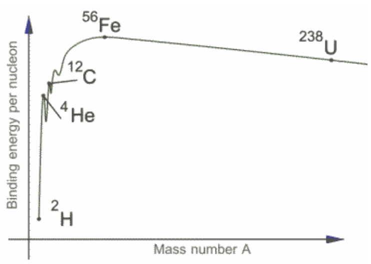
Thus, the **mass defect** of a nucleus is the difference between the observed rest mass of the constituent nucleons of the nucleus and its rest mass.

BE = (mass defect)c^2 = (mass of nucleons – rest mass of nucleus)c^2

BE per nucleon

The BE per nucleon is the average energy per nucleon needed to separate a nucleus into its respective individual nucleons, i.e.

$$\text{BE per nucleon} = \frac{\textit{total BE}}{\textit{nucleon number}}$$



The BE per nucleon allows us to compare the stability of different nuclei.

From the graph, Fe-56 has the highest BE/nucleon and is one of the most stable. Elements to the left of Fe combine to form more stable nuclide (i.e. **fusion**), and those to the right disintegrate into more stable nuclide (i.e. **fission**).

Nuclear Process

Nuclei may disintegrate or collide with each other to form new nuclei. In any nuclear process, **nucleon** number, **proton** number, **mass-energy**, and **linear momentum** must all be conserved.

Fission and Fusion

Fission refers to the disintegration of unstable nuclides to more stable nuclides, releasing energy in the process.

Fusion refers to the combination of nuclides to form heavier, more stable nuclides, releasing energy in the process. In nuclear fusion, light nuclei need to collide at very high speeds to overcome the large electrostatic repulsion of the nuclei.

Energy Considerations

In both fission and fusion, the total BE of products is larger than that of reactants. As such, the total mass defect of products is higher than that of reactants, and total rest mass of products is lower.

Thus, energy released = BE of pdts – BE of rxts. Alternatively, we can also use energy released = $(m_{reactants} - m_{products})c^2$.

Radioactive Decay

Radioactive decays are **spontaneous** (not triggered by external factors) and **random** (unpredictable). There are three types of decay, alpha α (^4_2He), beta β ($^0_{-1}e$), and gamma γ ($^0_0\gamma$) decay.

	α-particle	B-particle	γ-ray
Nature	Helium nucleus	Electron	E-M radiation
Notation	^4_2He	$^0_{-1}e$	$^0_0\gamma$

Radioactive Decay

	α-particle	B-particle	γ-ray
Charge	+2e	- e	0
Speed	0.1c	0.3 - 0.9c*	c
Relative Ionising ability	1 Very high	1/100 High	1/10 000 low
Relative penetrative properties	1 (stopped by thick paper/ 6cm of air)	100 (stopped by 3mm of aluminium)	10 000 (stopped by several cm of lead)

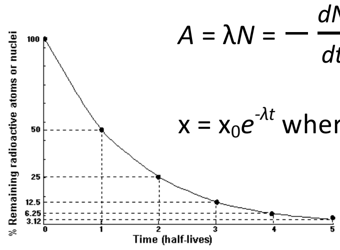
*Existence of the neutrino was predicted and proven later on to explain the range of speeds.

Background radiation: Any radiation detector placed in a location which has no apparent radioactive sources will usually register a background count.

Radioactive Decay Law

The **activity *A*** of a radioactive material is the rate of nuclear disintegration of its radioactive nuclei, while the **decay constant λ** is the probability of a radioactive nucleus disintegrating per unit time.

$$A = \lambda N = -\frac{dN}{dt} \qquad \lambda = \frac{\ln 2}{t_{1/2}}$$



$x = x_0 e^{-\lambda t}$ where x = N, A or C

The **half-life $t_{1/2}$** of a sample is the time taken for half of the radioactive nuclei to decay.

Biological Effects of Radiation

Radiation can lead to serious illnesses such as cancer, genetic defects or even death. Therefore, safety precautions must be in place when handling radioactive materials.

