The Structure of The Nucleus

Composition of Nuclei

The nucleus of an atom consists of protons and neutrons, which have approximately the same mass. The proton has a positive charge equal in magnitude to that of an electron. The neutron is uncharged.

	Mass (kg)	**Charge (C)**
Neutron	1.675×10^{-27}	No charge
Proton	1.673×10^{-27}	$+1.60\times10^{-19}$
*Electron**	9.11×10^{-31}	-1.60×10^{-19}

*Electrons are not found in nuclei, but are shown above for comparison of charges.

The term 'nucleon' refers to either a proton or a neutron.

The *atomic number Z* of an atom is the number of protons in the nucleus of the atom, and hence the positive charge of the nucleus in units of *e*, the charge of an electron.

The number of neutrons is denoted N .

The *mass number A* of an atom is the number of nucleons in the nucleus of an atom, and is given by $A = Z + N$.

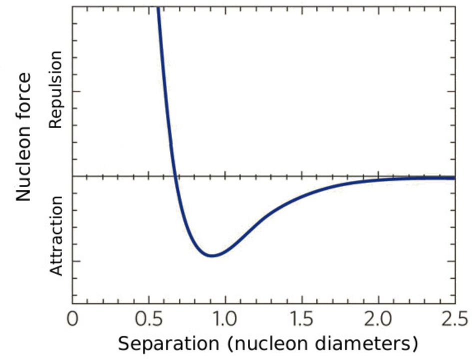
A nucleus of an element can be represented in the form ${}^{A}_{Z}\mathrm{X}$, where X represents the chemical symbol for the element.

For example ${}^{12}_{6}\mathrm{C}$ is a nucleus of the element carbon with six protons and six neutrons.

The Force Between Nucleons

Even though protons have a strong electrostatic repulsive force, they are able to hold together in the nucleus to form stable nuclei. This is possible because at short distances nucleons exert strong attractive forces on each other. These forces are independent of the nature of the nucleons.

The nucleon force becomes negligible at separations of more than a few nucleon diameters, and become repulsive at extremely short distances, as shown on the graph below:



Isotopes

Nuclei of a given element all have the *same* number of *protons*. In neutral atoms this is also the number of electrons.

Nuclei of a given element may have *different* numbers of *neutrons*. These nuclei are the isotopes of the element.

Isotopes of a given element are chemically identical but have different masses. This is because the chemical properties of any given element depend only on the electronic structure (protons and electrons). Neutrons have no charge, so they do not interfere with the electronic structure.

Mass Defect and Binding Energy

Mass *m* and energy *E* are related according to $E = mc^2$, where *c* is the speed of light.

Accurate measurements have shown that the mass of a nucleus is less than that of its individual nucleons. The difference is called the 'mass defect' (Δm).

A large amount of energy is absorbed when the nucleons contained in a nucleus are separated; total mass increases. When nucleons are combined to form a new nucleus, a large amount of energy is released and total mass decreases.

The minimum energy necessary to separate a nucleus into its constituent nucleons is called the 'binding energy' (E_b) of the nucleus, and corresponds to the mass defect.

Binding energy is often given in MeV (mega-electron volts), where 1 MeV is 1×10^6 eV. The relationship between binding energy and mass defect is $E_b = \Delta mc^2$

Conservation Laws in Nuclear Reactions

A *nuclear reaction* takes place when nucleons become a nucleus (or part of a nucleus) or nucleons are separated from a nucleus.

Reactants are the pieces *before* the reaction, *products* are the pieces *after* the reaction.

In a nuclear reaction:

- the total charge and the total number of nucleons are *conserved*,
- the total mass of the products is *different* from the total mass of the reactants,
- the total energy (including the energy associated with the mass) is conserved,
- momentum is conserved.

Summary of steps to find energy absorbed or released in a nuclear reaction:

1. Calculate the mass of the reactants
2. Calculate the mass of the products
3. Decide if mass was lost (energy released) or gained (energy absorbed)
4. Use $E_b = \Delta mc^2$ to calculate the energy released or absorbed
5. Divide by 1.6×10^{-13} to convert to MeV

Conservation of Momentum in Nuclear Reactions

When energy is released during a nuclear reaction there are various forms it can take, for example photons or kinetic energy. In the case of kinetic energy, it is important to note that the law of conservation of momentum is always obeyed.

Particles of smaller mass will acquire more of the kinetic energy during a reaction. The reason for this is that for two products, in order for momentum to be conserved they must both move off in opposite directions with *equal magnitude* of momentum. A product with less mass then will have *more velocity*, since $p = mv$. Since $K = \frac{1}{2}mv^2$, the smaller product will have more kinetic energy.

$$K = \tfrac{1}{2}mv^2$$
$$\therefore mK = \tfrac{1}{2}m^2v^2 \quad \{\text{multiplying both sides by } m\}$$
$$\therefore mK = \tfrac{1}{2}(mv)^2$$
$$\therefore mK = \tfrac{1}{2}p^2 \quad \{p = mv\}$$
$$\therefore K = \frac{\tfrac{1}{2}p^2}{m}$$

Since p is constant and K is inversely proportional to m, K will be bigger for smaller m.
That is, smaller particles acquire more of the kinetic energy.

The Production of Medical Radioisotopes

A nucleus can have its composition changed by the absorption of particles such as neutrons ${}^{1}_{0}n$, protons ${}^{1}_{1}H$ and deuterons ${}^{2}_{1}H$. In these interactions momentum must be conserved, which often means that a particle is ejected from the newly formed nucleus.

A radioisotope is an unstable (radioactive) isotope which will spontaneously break down, emitting radiation.

The medical radioisotope phosphorous-32, also written ${}^{32}_{15}P$, is used in scientific research and medical treatments. It is occasionally used to treat some rare cancers but its most common medical use is the treatment of excess blood cells, since phosphorus-32 suppresses the production of red blood cells in bone marrow.

The production of phosphorus-32 is achieved by allowing the neutrons emitted from a nuclear reactor to hit nuclei of sulphur-32. The sulphur nuclei eject a proton in the process and the desired radioisotope is created. This process can be shown by the equation below.

$${}^{1}_{0}n + {}^{32}_{16}S \longrightarrow {}^{32}_{15}P + {}^{1}_{1}H$$

The medical radioisotopes fluorine-18 and oxygen-15 are commonly used in positron emission tomography (PET) scans and may be produced in hospitals, using cyclotrons.

To create fluorine-18, hydrogen nuclei (protons) are accelerated to high energies in a cyclotron and then allowed to bombard oxygen-18 nuclei. A neutron is displaced from the oxygen and the fluorine absorbs the proton, as shown below:

$${}^{1}_{1}H + {}^{18}_{8}O \longrightarrow {}^{18}_{9}F + {}^{1}_{0}n$$

A similar process is used to create oxygen-15, except that in this case nitrogen-14 is bombarded with deuterons (hydrogen-2 nuclei). The deuteron's proton is absorbed, and a neutron is emitted during the reaction, as shown below:

$${}^{2}_{1}H + {}^{14}_{7}N \longrightarrow {}^{15}_{8}O + {}^{1}_{0}n$$

The process of positron emission tomography is explained in the Radioactivity topic.