Department of Medical Physic

Basic Physics, Part 1

Lecture 4

Medical physics

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Outlines

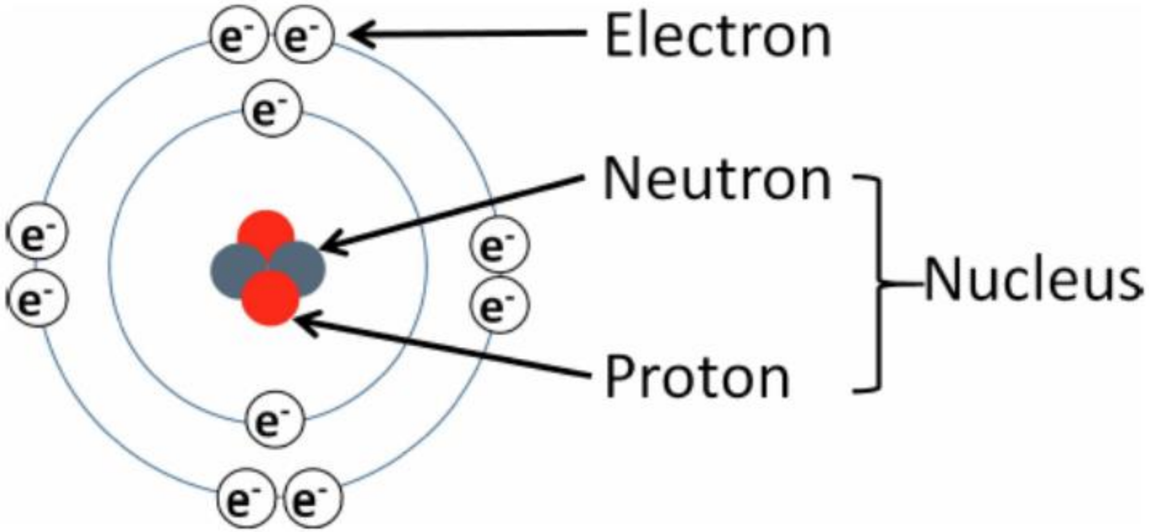
1- Basic science

> Atomic structure
> Radioactive decay
> Electromagnetic radiation

> Atomic structure

The Rutherford-Bohr model of an atom

Overview



Model of an atom

Atoms consist of :

- **Nucleus:** contains positive protons (p) and neutral neutrons (n)
- **Electrons:** circle the nucleus within energy “shells”

Where is the central mass of the atom ?

- Nucleus

Table : Some fundamental particles of the atom

	Relative mass	*Relative charge*	*Symbol*
Nucleons			
▪ *Neutron*	*1*	*0*	n
▪ *Proton*	*1*	*+ 1*	p
Extra-nuclear			
▪ *Electron*	*1 / 1840 (0.00054)*	*- 1*	e^-, β^-
Other			
▪ *Positron*	*1 / 1840 (0.00054)*	*+ 1*	e^+, β^+
▪ *Alpha particle*	*4*	*+ 2*	α

• The diameter of the nucleus of an atom is about 5 x 10^{-15} m.

The diameter of the entire atom is about 5 x 10^{-10} m (100,000 times larger)

- Most of an atom is an empty space.

• Rutherford and Bohr model → an atom is a massive positively charged nucleus surrounded by electrons in orbits of specific diameters.

Nucleus:

- Has a positive electrical charge, and contains almost all the mass of an atom.
- Made of several types of particles "**NUCLEONS"** only **protons** & **neutrons** considered.
- **Atomic number "Z" →** number of protons in the nucleus → synonymous with element name.
- **Mass number "A" →** total number of protons and neutrons in the nucleus.
- The strong nuclear force is responsible for holding the nucleus together.
- All atoms of an element have the same atomic number (Z), but may have different mass numbers (isotopes).

Describing an atom

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

Atoms are displayed in the format shown where:

A = mass number (p + n)
Z = atomic number (protons)
X = chemical symbol of the atom

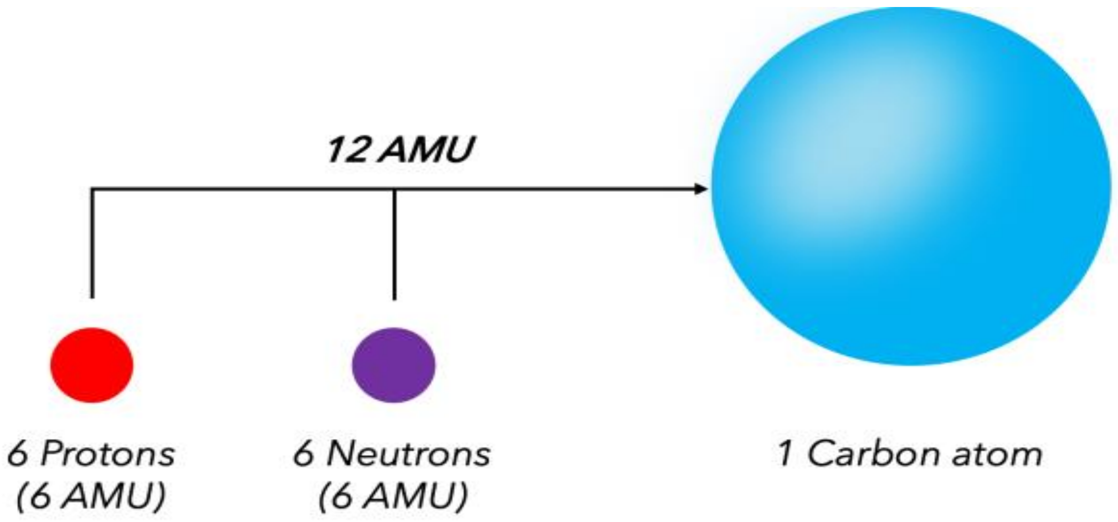
The neutrons and protons (collectively called nucleons) give the atom its mass. This isn't the actual mass but that relative to other atoms.

1 atomic mass unit (amu) = 1/12 the mass of a carbon -12 atom
The amu's of different components of the atoms are shown in the table below:

	Relative mass	Charge	Symbol
Neutron	1	0	n
Proton	1	+1	p
Electron	0.0005	-1	e-

The Atomic Mass Unit

An Atomic Mass Unit (AMU) is a unit of mass relative to a single constituent of a Carbon atom.
1 AMU is equal to 1/12 the mass of a Carbon atom.



Since there are 12 nucleons in an atom of Carbon – 6 protons and 6 neutrons – let's assume that 1 AMU is equal to either 1 proton or 1 neutron.

electron orbits and energy levels:

- ➔ An atom is composed of a central positive nucleus + electrons with negative charges
revolving around the nucleus in circular orbits.
- ➔ A neutral atom contains an equal number of protons and electrons.
- ➔ The electron orbits are designated by letters: K, L, M, N, O, and so on.
- ➔ The atomic system allows 2 electrons in the first orbit, 8 in the second, 18 in the third,
32 in the fourth, and 50 in the fifth **(2** N^2**)**.
- ➔ An electron in the K shell is called a K electron. L electrons are in the L shell.

Electrons

Types of electrons

Electrons are either bound or free.

• Bound electrons: These are the electrons that are held in orbit around the nucleus in the electron shells by the attractive force of the positive nucleus.

• The binding energy is the positive energy required to overcome the pull of the nucleus and release the electron from the shell. This is of the same magnitude as the actual (negative) energy of the electron that is released if the electron is freed.

• Free electrons: These are the electrons that are not bound in an electron shell around a nucleus. They have a kinetic energy of:

$$\text{Kinetic energy} = \tfrac{1}{2}mv^2$$

Where:

m = mass , v = velocity

The actual binding energy of electrons is expressed in electron volts (eV) or KeV (1KeV = 1000 eV)

$$1\ \text{eV} = 1.6022 \times 10^{-19}\ \text{joules}$$

- Binding energy for K- shell is greater than L-shell , EK > EL > EM.

in creasing the atomic number, increase the binding energy.
The binding force is inversely proportional to the square of the distance between the nucleus and electron ⟶ K electron has a larger binding than an L electron.

Never greater than 100 keV.

- The binding energy depends on

1. The shell (EK > EL > EM ...).
2. The element (↑ Atomic number → ↑ binding energy)

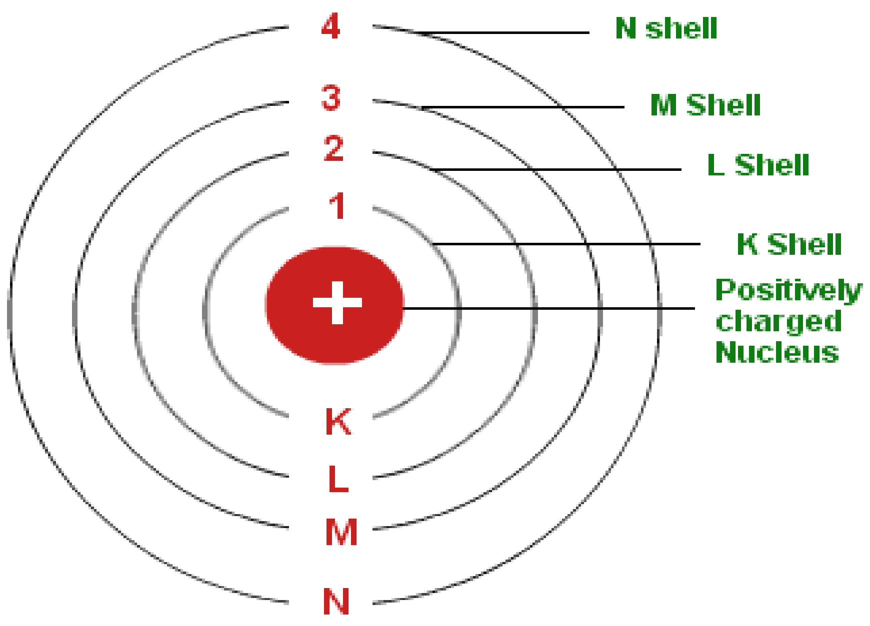
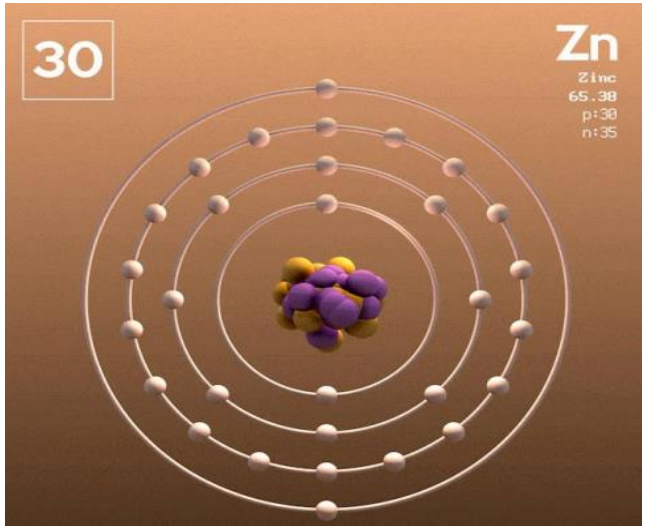


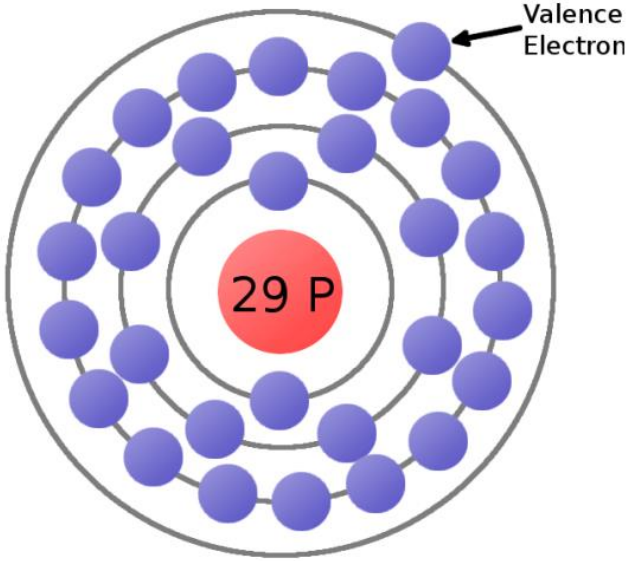
Table: Atomic number (Z) and K-shell binding energy (E_k) of various elements

Element	Z	E_K (keV)
Aluminium	13	1.6
Calcium	20	4
Molybdenum	42	20
Iodine	53	33
Barium	56	37
Gadolinium	64	50
Tungsten	74	70
Lead	82	88

Valence shell:

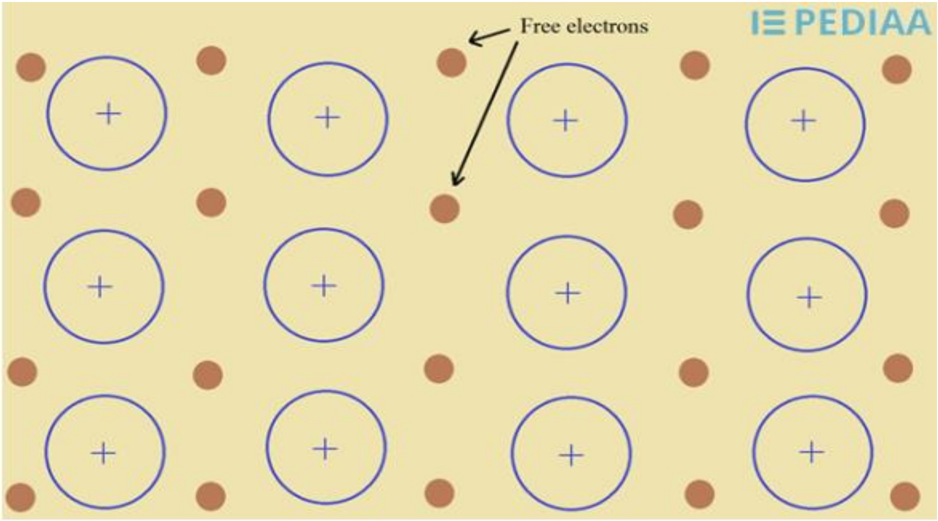
- Outermost shell.
- Concerned with the chemical, thermal, optical properties of the element.
- Can’t have more than 8 electrons (called free electrons)





Free and valence electrons

Free Electrons: Free electrons are electrons that are not attached to an atom



VALENCE ELECTRONS
VERSUS
FREE ELECTRONS

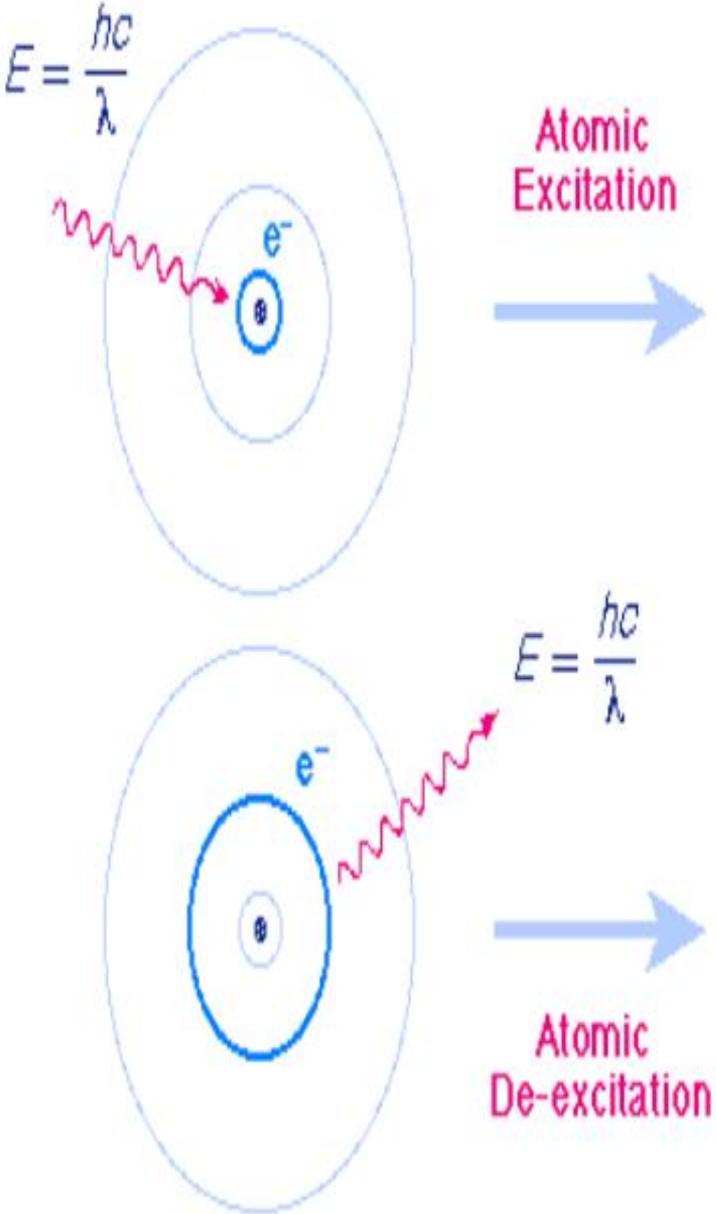
Valence electrons are the electrons present in the outermost orbitals of an atom	Free electrons are electrons that are not attached to an atom
Have less attraction towards the nucleus of an atom	Have no attraction towards the nucleus of an atom
Responsible for the chemical bonding of an atom	Not involved in chemical bonding
Cannot conduct heat and electricity	Responsible for the conduction of heat and electricity
The number of valence electrons is an elemental property	The number of free electrons is a lattice property

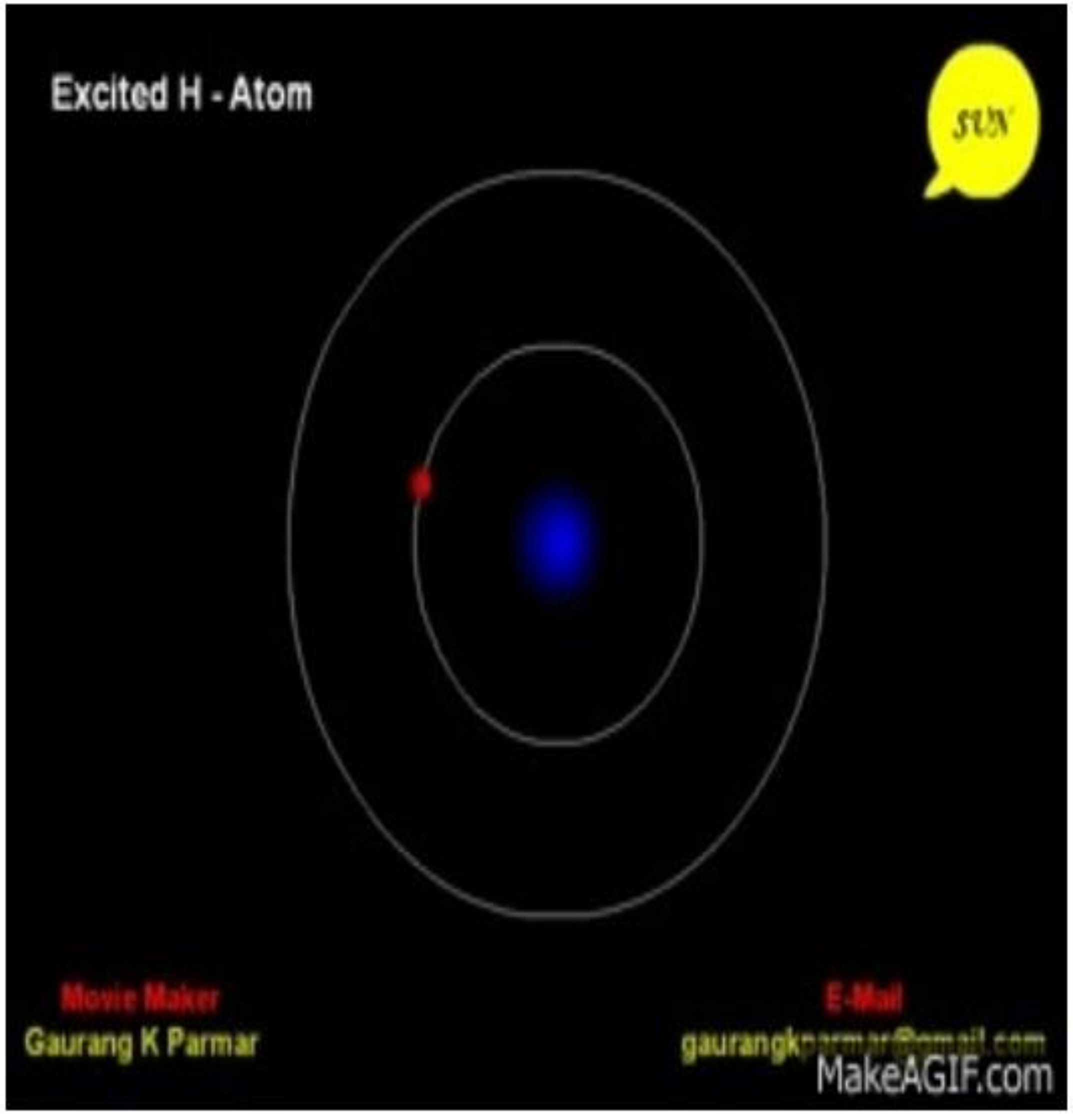
Ionization & Excitation:

- Ionized atom → if one of its electrons has been completely removed → ion pair "electron + positive ion“

- Excited atom → if an electron is raised from one shell to a farther one with the absorption of energy → the atom has more energy than normal.

When it falls back → energy is re-emitted as a single 'packet' of energy or light photon.


$E = \frac{hc}{\lambda}$
e⁻
Atomic
Excitation
e⁻
e⁻
$E = \frac{hc}{\lambda}$
Atomic
De-excitation
e⁻


Excited H - Atom
Movie Maker
Gaurang K Parmar
E-Mail
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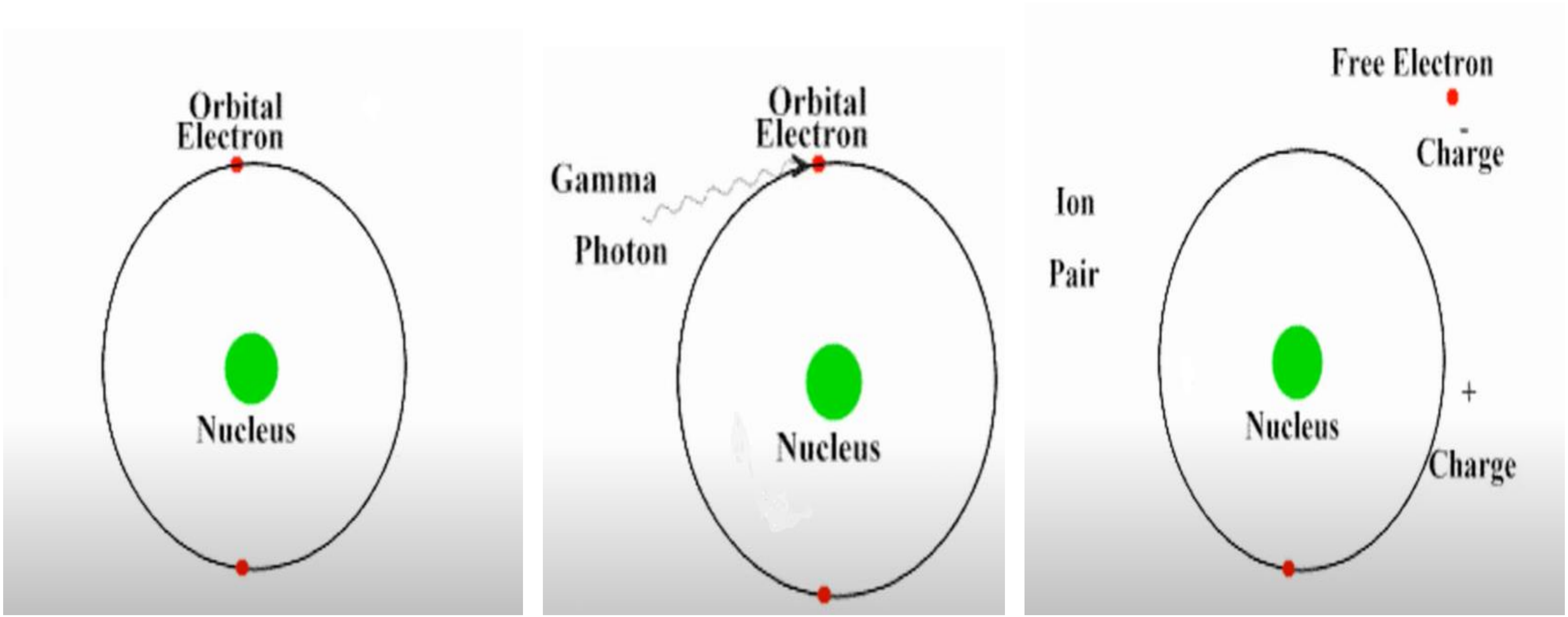
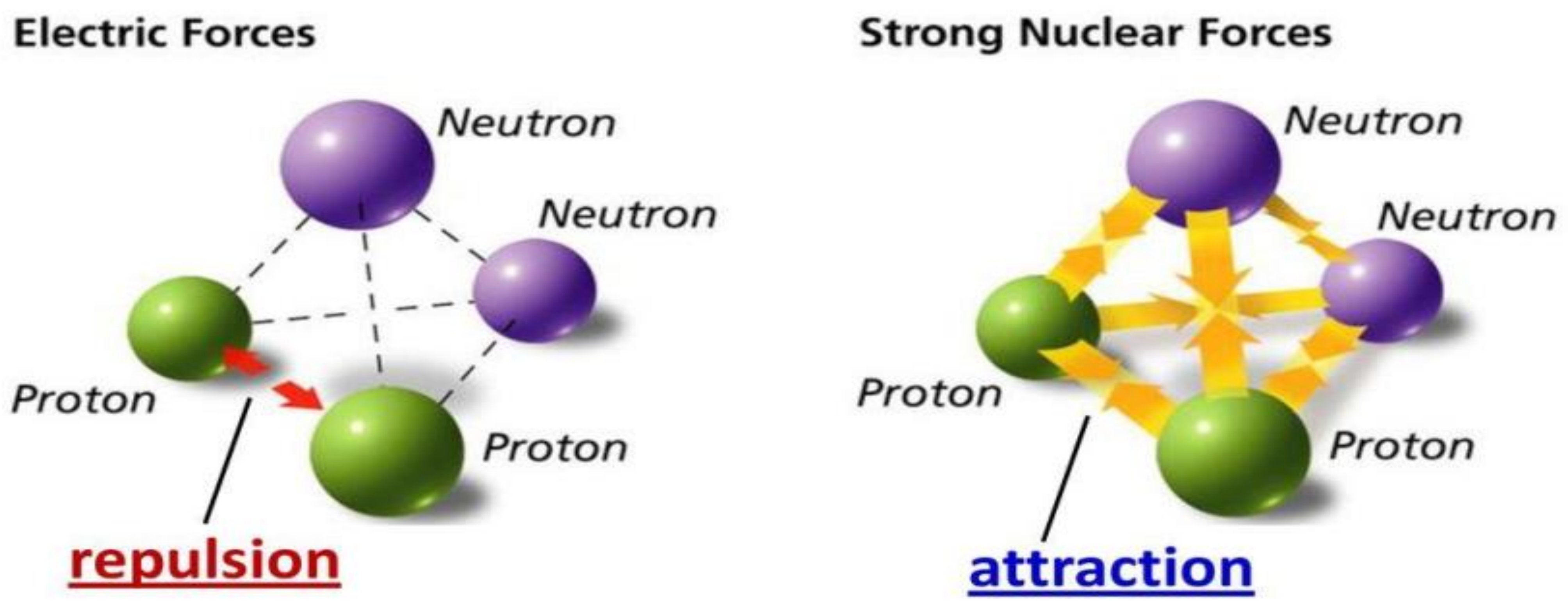

Orbital
Electron
Nucleus
Gamma
Photon
Orbital
Electron
Nucleus
Free Electron
-
Charge
Ion
Pair
Nucleus
+
Charge

1.2 Nuclear stability

- The nucleus is composed of protons and neutrons. The protons repel each other (electrostatic force) but the nucleus is kept held together by the strong nuclear force.
- Strong nuclear force: There is a strong force of attraction at distances between nucleons of <10^{-15} m which changes to a repulsive force at < 10^{-16} m. The nucleons are kept apart at a distance of ~ 5 x 10^{-16} m, the distance at which there is the greatest attraction.
- Electrostatic force: this is the force of repulsion between protons. At distances of 10^{-15} to 10^{-16} m the strong attractive interaction (strong nuclear force) is much greater than the repulsive electrostatic force and the nucleus is held together.

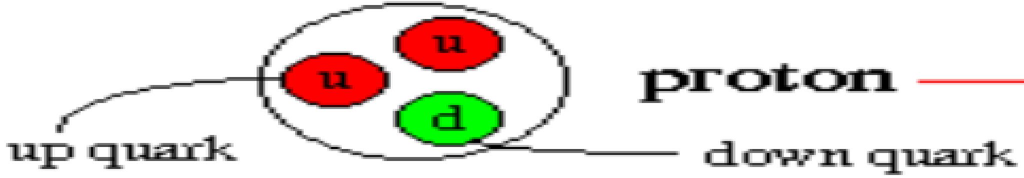
Nuclear Forces

Do nuclei contain attractive or repulsive forces?

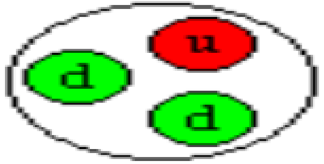


Atomic Nuclei = Combinations of Quarks

<u>Baryons</u> = particles made of 3 quarks



proton —— charge = +1 (2/3+2/3−1/3)



neutron —— charge = 0 (2/3−1/3−1/3)

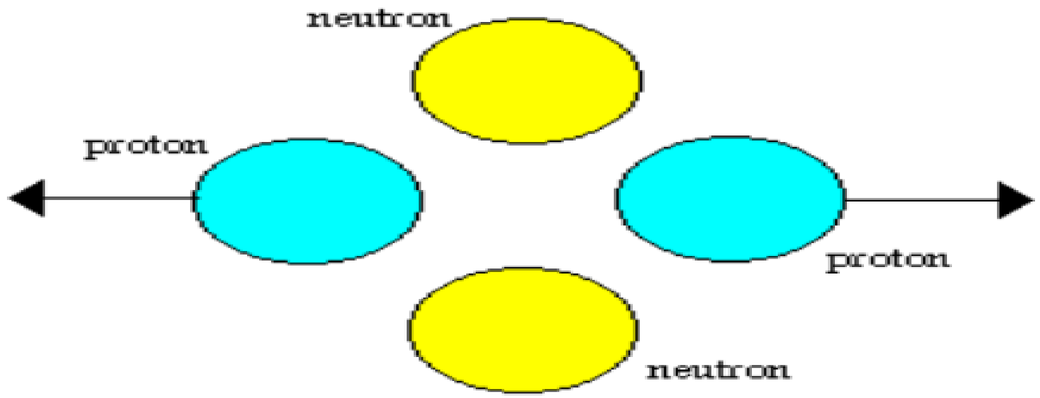
<u>Mesons</u> = particles made of 2 quarks

pion —— charge = +1 (2/3+1/3)

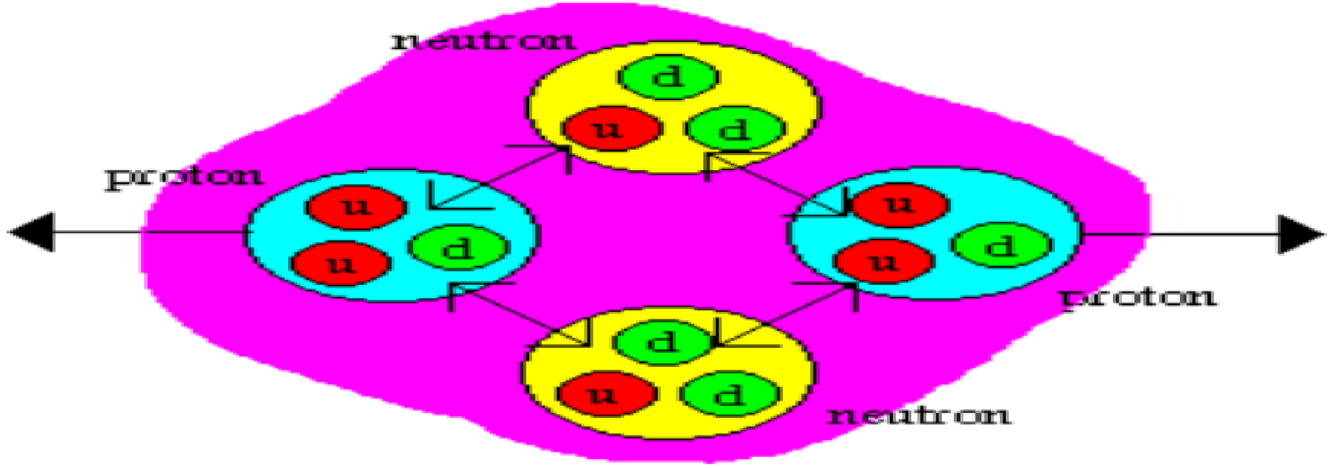
What binds quarks together?

the strong force carried by gluons

Color Force

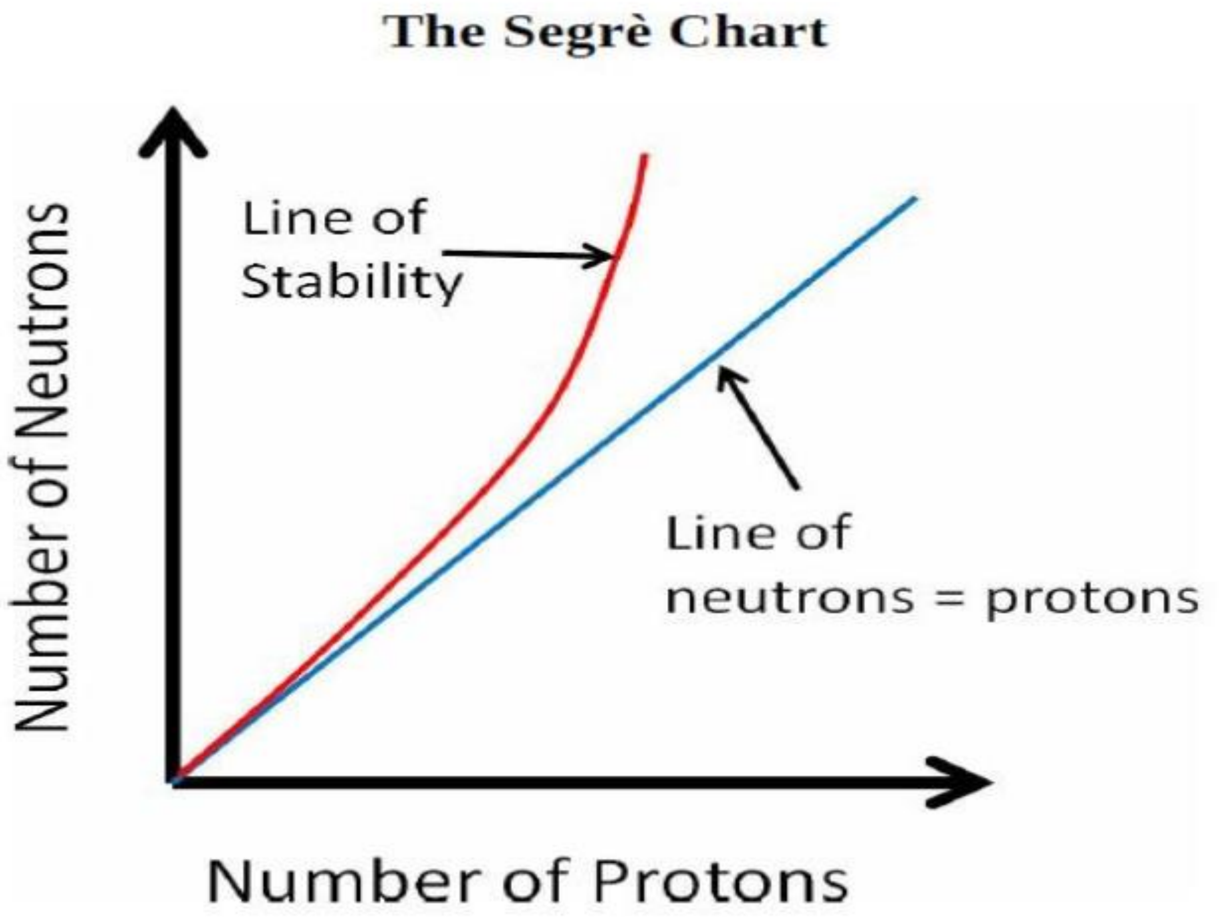


An early dilemma for quantum mechanics was “how dose the nucleus of an atom hold together with the repulsive electrostatic forces of the protons pulling it apart”



The answer is that the color force between quarks in the proton and neutron produce the strong force, which overcomes the electrostatic force

Segrè chart



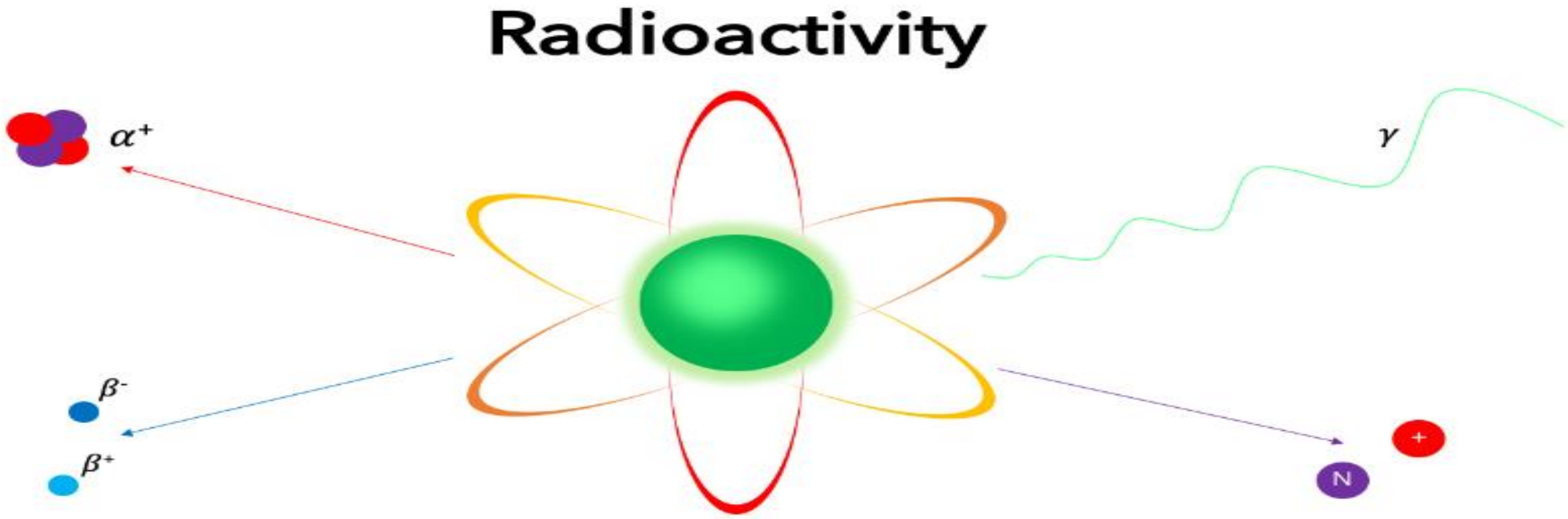
The Segré chart shows the proportion of neutrons needed to keep the nucleus stable as the number of protons increases (the "line of

As the atomic number increases (i.e. the number of protons) more neutrons are required to prevent the electrostatic forces pushing the protons apart and to keep the nucleus stable.

If an atom has too many or too few neutrons and does not lie upon the "line of stability", it becomes unstable and decays to a more stable form. This is the basis of radioactivity and is discussed next in the "electromagnetic radiation" chapter.

> Radioactive decay

Radioactive decay generally involves the emission of a charged particle or the capture of an electron by the nucleus to form stable nuclides.
The amount of decay = the radioactivity = the number of nuclear transformations per second



Radiation is energy transmitted in the form of waves or particles. ***Light*** and ***Heat*** are forms of radiation.

Radioactive Decay is the ***spontaneous*** emission of this energy due to nuclear instability.

Nomenclature

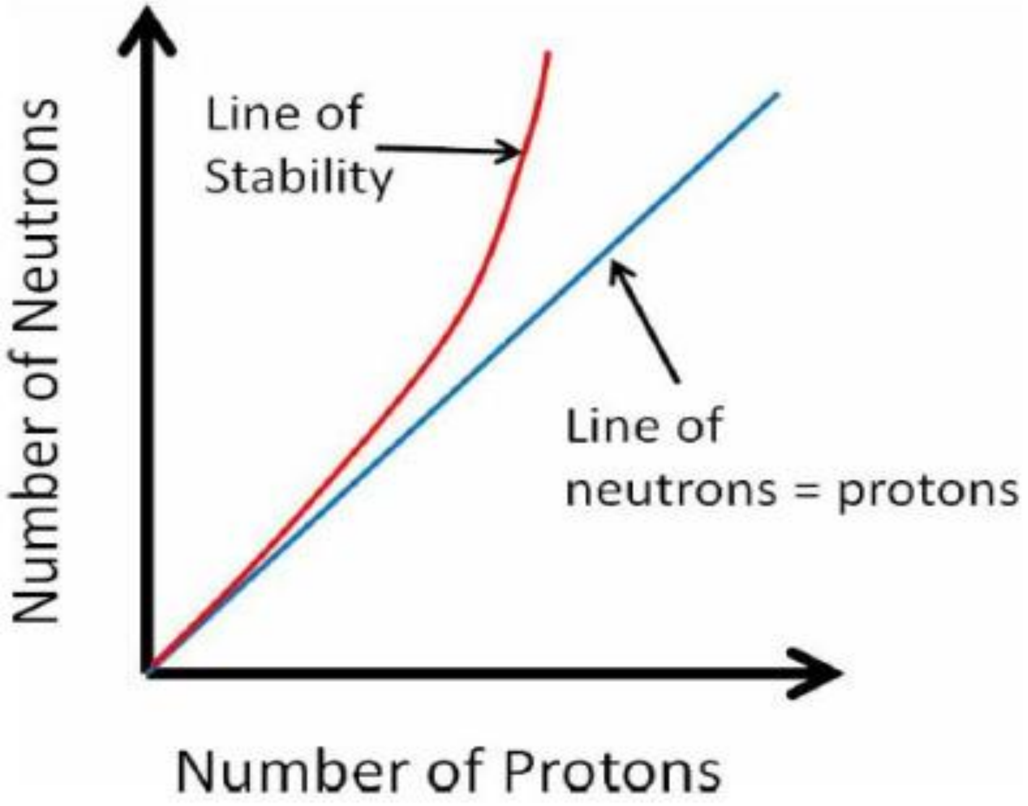
Nuclide	**Nuclear species with specific number of neutrons and protons that exists in a defined nuclear energy state (e.g. 99mTc is a different nuclide to 99Tc)**
Radionuclide	**Radioactive nuclide**
Metastable Radionuclide	**A radionuclide that exists for a long time in a higher energy state before falling to ground state (e.g.99mTc)**
Isomer	**The metastable version of a nuclide (isomer) of a nuclide e.g. 99mTc is an isomer of 99Tc.**
Isotone	**Nuclides with the same number of neutrons (isotone) but with a different number of protons**
Isotope	**Nuclides with the same number of protons (isotope) but with a different number of neutrons**

N.B. the number of protons determines the element of an atom. You can change the number of neutrons (and, therefore, the mass number) and the atom will still be the same element.

Nuclear stability

In the chapter on "Atomic structure" we covered nuclear stability and referred to the Segré chart.
What the line of stability shows is that as the number of protons increases, the proportion of neutrons needed to keep the nucleus stable increases. When the nuclide doesn't lie on the line of stability it becomes unstable and radioactive.

The line of stability - Segré chart



The Segré chart shows the proportion of neutrons needed to keep the nucleus stable as the number of protons increases (the "line of stability")

Isotope

Isotopes of an element are nuclides that have the same number of protons (atomic number), position in the periodic table, and chemical and metabolic properties but a different number of neutrons, mass number (protons plus neutrons), density and other physical properties.

Nuclear Reactor: atoms can’t be separated chemically as, all have the same Z

$$^{98}\mathrm{Mo} + \mathrm{n} \rightarrow {}^{99}\mathrm{Mo}.$$

Cyclotron : atoms can be separated chemically as, all have different Z

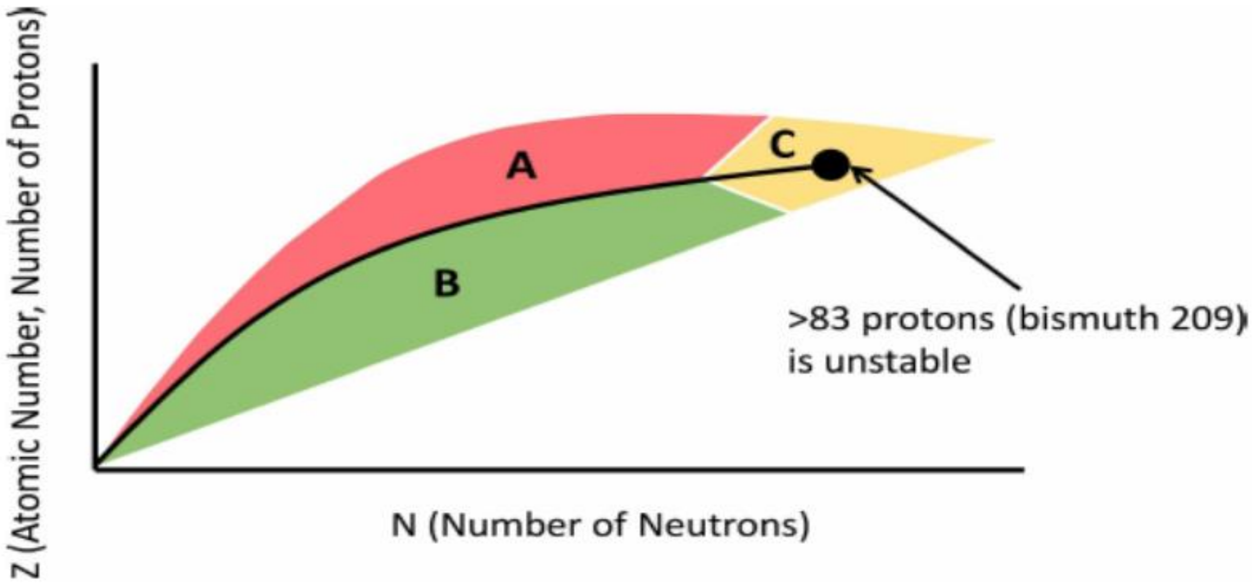
$$^{18}\mathrm{O} + \mathrm{p} \rightarrow {}^{18}\mathrm{F} + \mathrm{n}.$$

Radioactive fission products may be extracted from the spent fuel rods of nuclear reactors.

$$^{238}U \rightarrow {}^{99}Mo + \text{other fission by-products.}$$

As the molybdenum is different chemically from the other products, it can be separated and prepared in a very pure form.

Decay model of nuclides



The decay model of nuclides above includes all nuclides: stable and radioactive. Nuclides in area **A** have too few neutrons, in area **B** have too few protons, and in area **C** are very heavy with excess protons and neutrons. The area the nuclide lies in determines the type of radioactivity the nuclide goes through to become stable and is discussed below.

Radioactive decay

The decay of a nuclide is exponential i.e. it theoretically never reaches zero. The S.I unit of radioactivity is the Becquerel (Bq):

$$1\ \text{Bq} = 1\ \text{transformation per second}$$

Types of radiation

When a nuclide undergoes radioactive decay it breaks down to fall into a lower energy state expending the excess energy as radiation. The radioactivity released can be:

1. **Alpha particles**
2. **Beta particles**
3. **Gamma particles (or photons)**
4. **Others**