Introduction to Nuclei – I

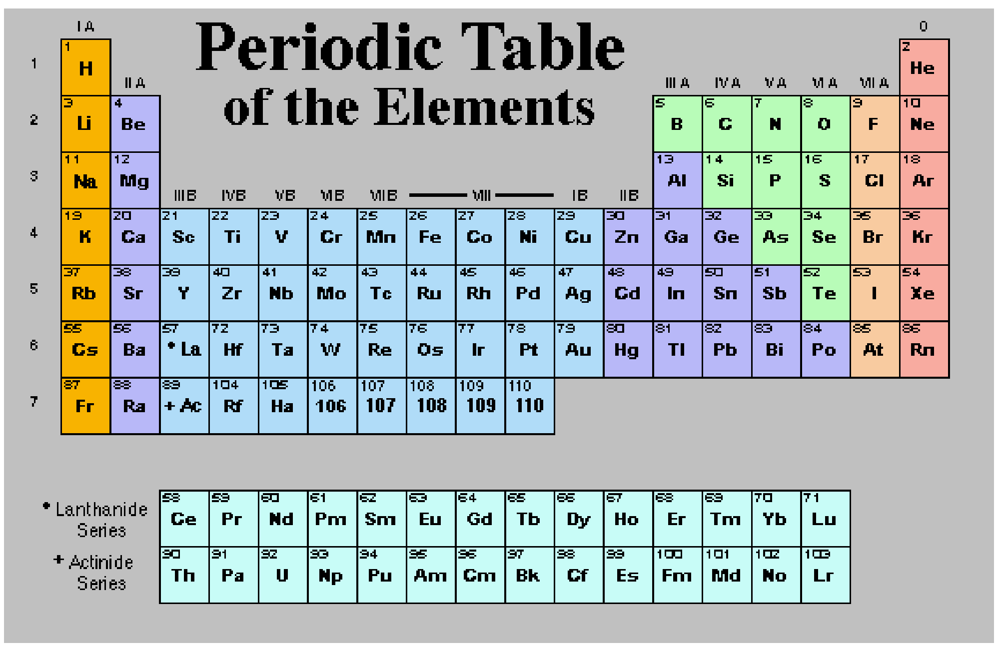
(The discovery)

“The opposite of a correct statement is a false statement. But the opposite of a profound truth may well be another profound truth”

- Niels Bohr

The Atomic Nucleus

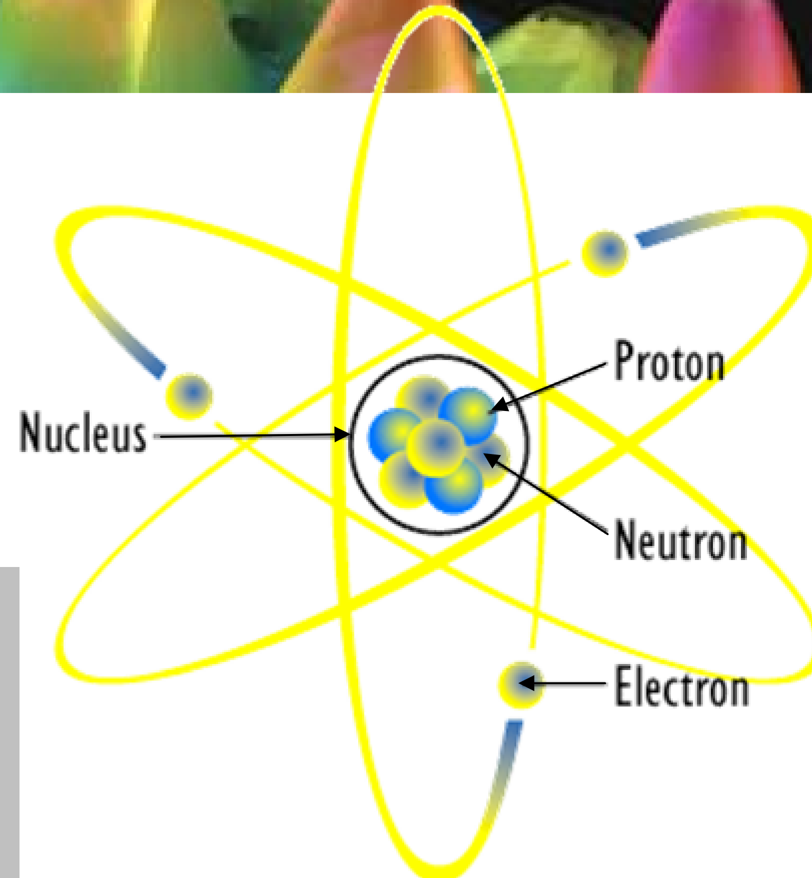
An atom is the smallest particle that characterize a chemical element.



Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 + Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



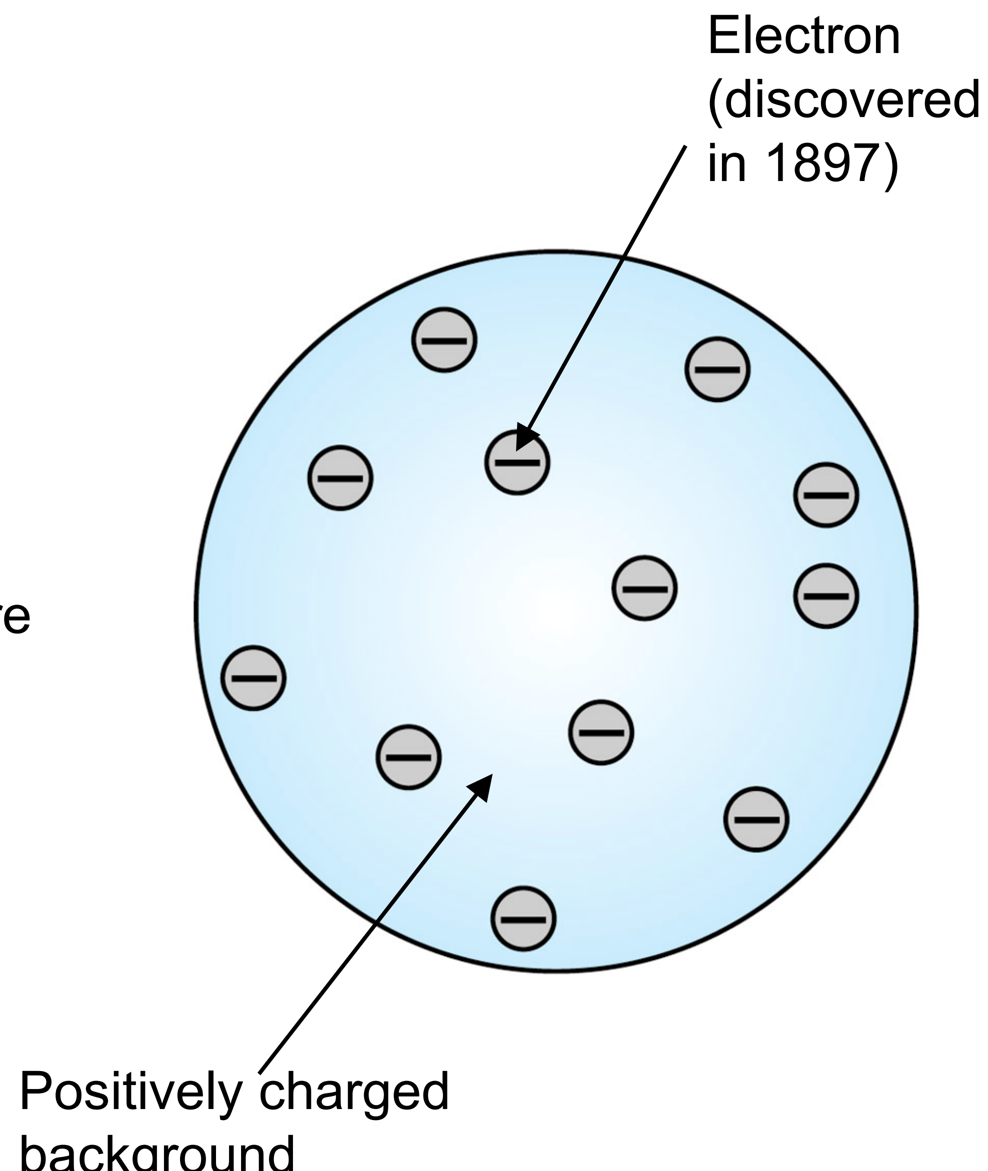
It consists of a heavy <u>NUCLEUS</u> with a POSITIVE electric charge, which is surrounded by a swarm of much lighter particles, the NEGATIVELY charged <u>ELECTRONS</u>.

Knowledge of atoms in 1900

Thomson's Atomic Model

Thomson's "**plum-pudding**" model of the atom had the positive charges spread uniformly throughout a sphere the size of the atom, with electrons embedded in the uniform background.

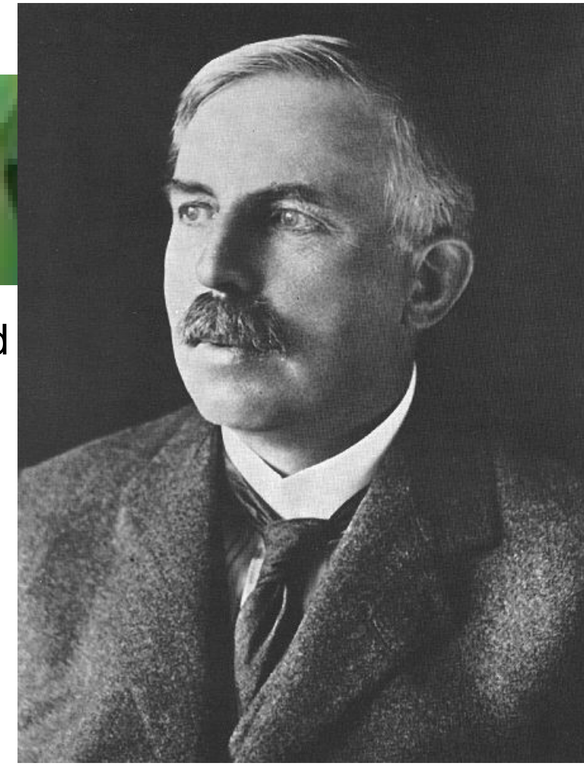
But cannot explain the discrete lines in atomic spectra

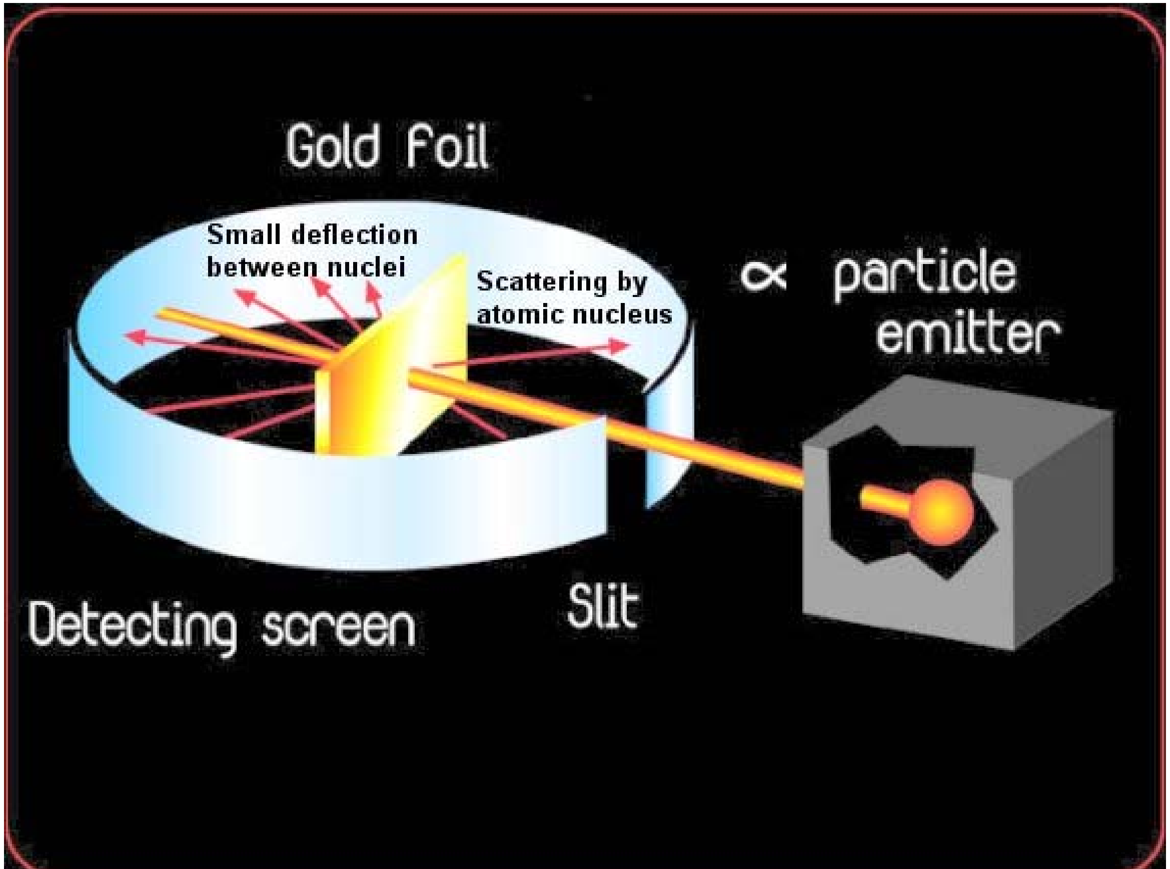


Discovery of Nucleus : The dawn of Nuclear Physics

Rutherford's Scattering Experiment (1909)

Ernest Rutherford (1871-1937)

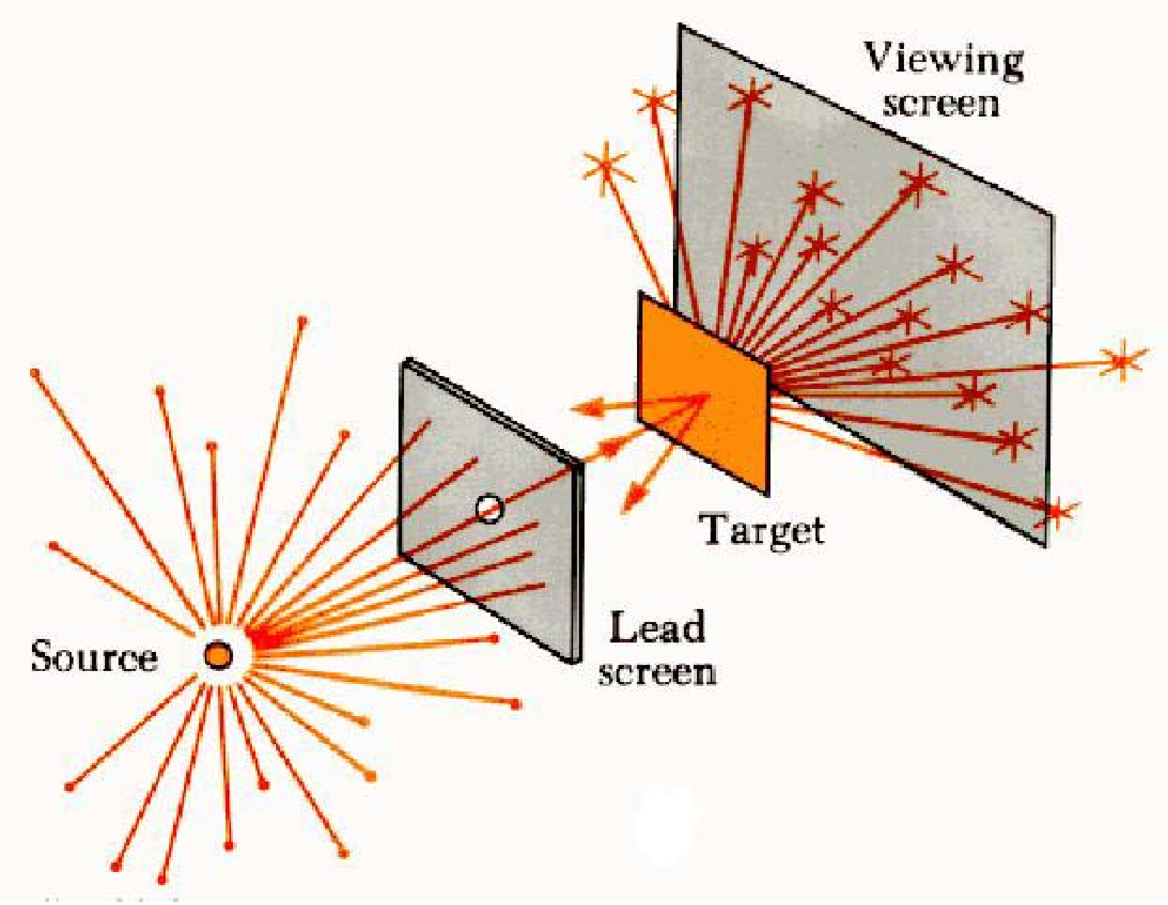




Geiger, and Marsden bombarded a thin gold foil with alpha particles (a helium atom with its electron stripped off).

Experiments of Geiger and Marsden (1909)

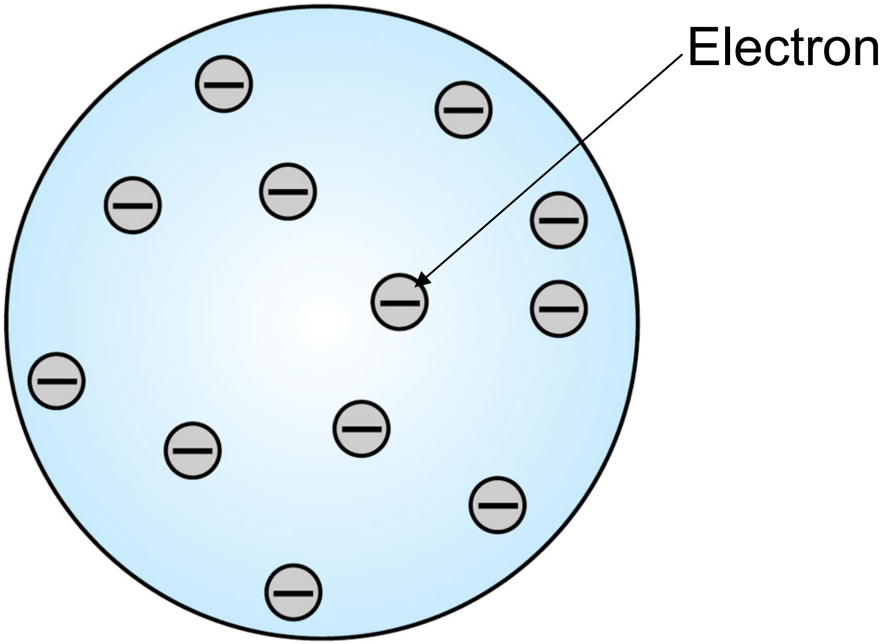
They found that many α particles were scattered from thin gold-leaf targets at backward angles greater than 90°.



“It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you”

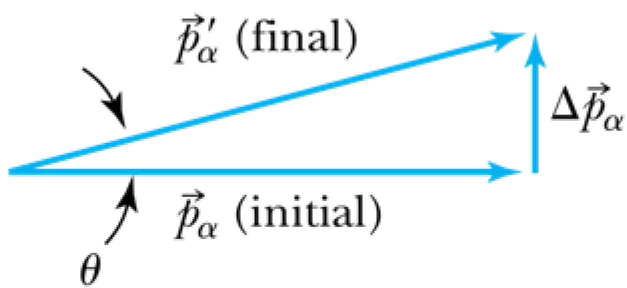
- E. Rutherford

Electrons can't back-scatter α particles.



Calculate the maximum scattering angle— corresponding to the maximum momentum change.

$$\Delta p_{\max} = 2m_e \mathrm{v}_\alpha$$



$$\theta_{\max} = \frac{\Delta p_\alpha}{p_\alpha} = \frac{2m_e \mathrm{v}_\alpha}{M_\alpha \mathrm{v}_\alpha} = 2.7\times10^{-4}\ \mathrm{rad} = 0.016^\circ$$ too small!

Try multiple scattering

If an α particle is scattered by N atoms: $\langle\theta\rangle_{total} \approx \sqrt{N}\theta$

N = the number of atoms across the thin gold layer, $t = 6 \times 10^{-7}$ m:

$$n = \frac{\text{Number of molecules}}{\text{cm}^3} = [\text{Avogadro's no. (molecules/mol)}] \times \left[\frac{1}{\text{gram} - \text{molecular weight}}\left(\frac{\text{mol}}{\text{g}}\right)\right]\left[\text{density}\left(\frac{\text{g}}{\text{cm}^3}\right)\right]$$

$$= \left(6.02\times10^{23}\frac{\text{molecules}}{\text{mol}}\right)\left(\frac{1\text{ mol}}{197\text{ g}}\right)\left(19.3\frac{\text{g}}{\text{cm}^3}\right)$$

$$= 5.9\times10^{22}\frac{\text{molecules}}{\text{cm}^3} = 5.9\times10^{28}\frac{\text{atoms}}{\text{m}^3}$$

The distance between atoms, $d = n^{-1/3}$, is: $d = (5.9\times10^{28})^{-1/3}\text{m} = 2.6\times10^{-10}\text{m}$

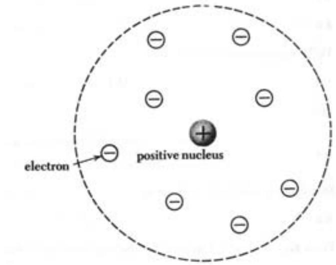
$$N = t/d = \frac{6\times10^{-7}\text{m}}{2.6\times10^{-10}\text{m}} = 2300 \text{ atoms}$$

$$\langle\theta\rangle_{total} = \sqrt{2300}(0.016°) = 0.8°$$

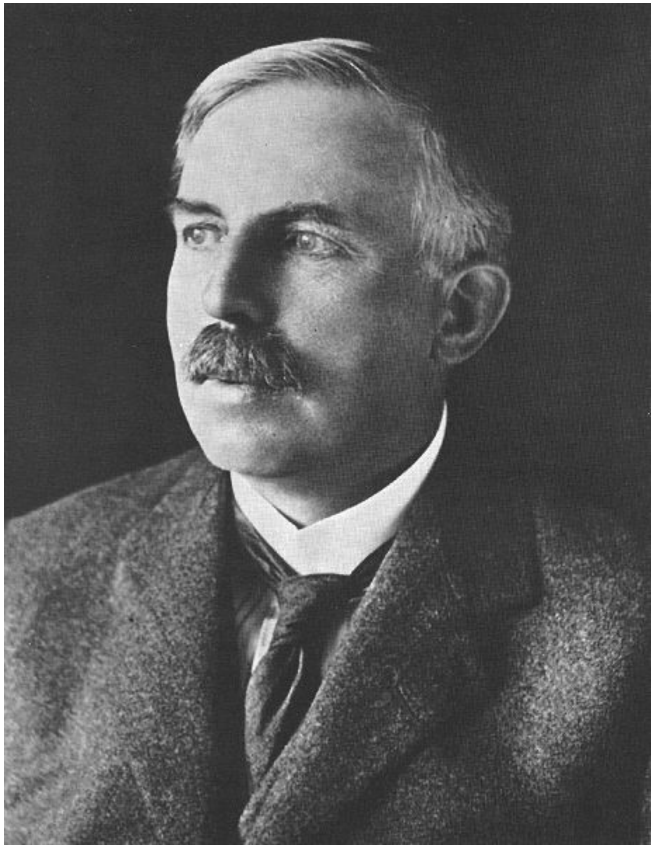
still too small!

Rutherford's Atomic Model (1911)

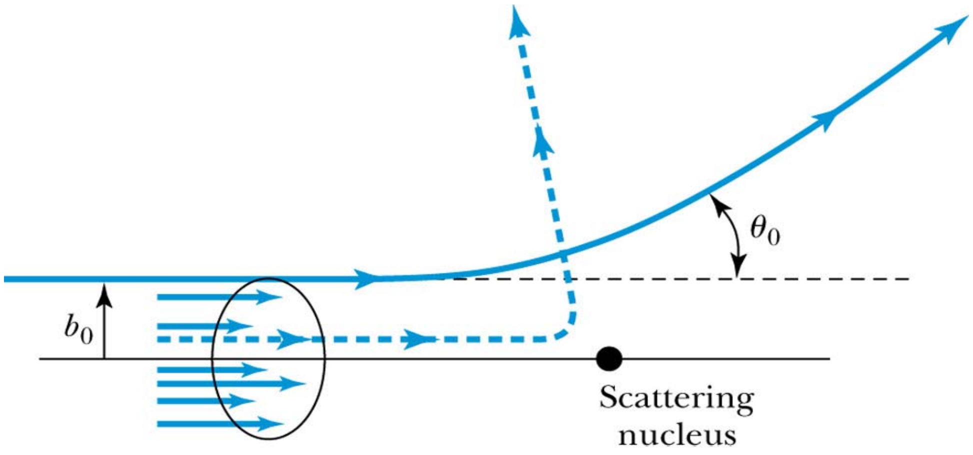
$\langle \theta \rangle_{total} = 6.8°$ even if the α particle is scattered from all 79 electrons in each atom of gold.



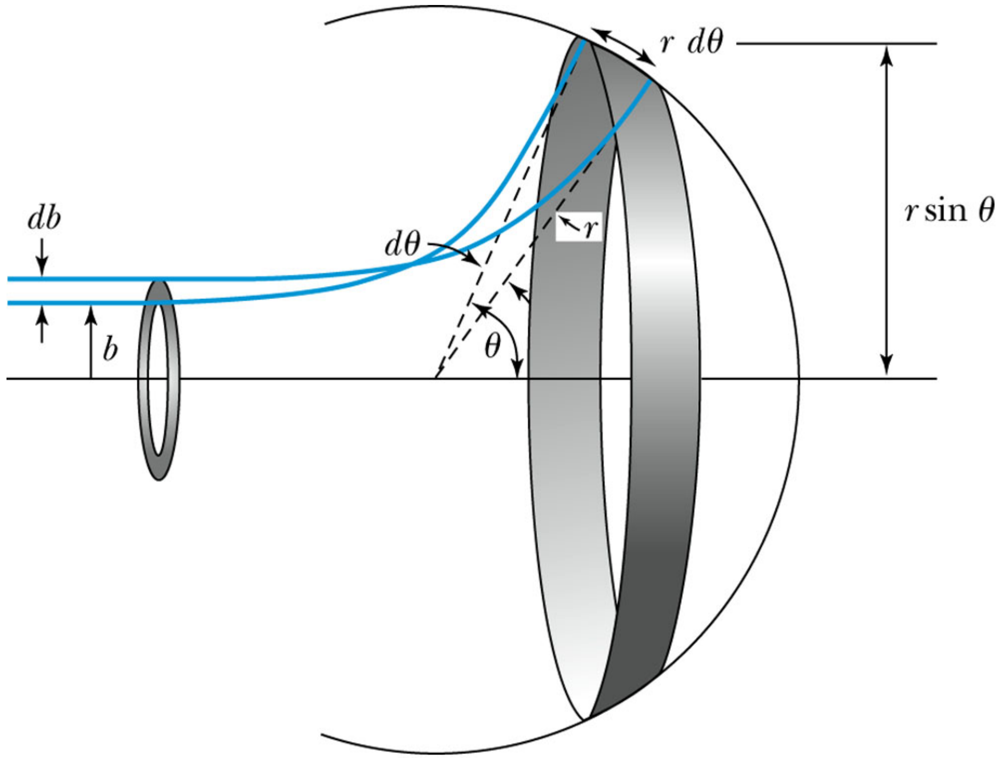
Ernest Rutherford
(1871-1937)

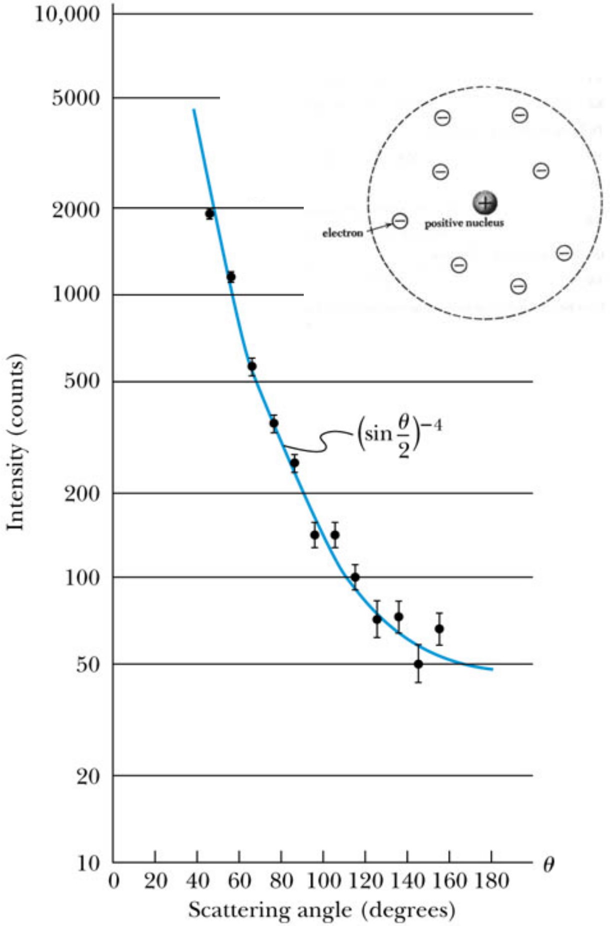


Rutherford proposed that an atom should have a positively charged core (**nucleus**) surrounded by the negative electrons.



Rutherford Scattering Formula

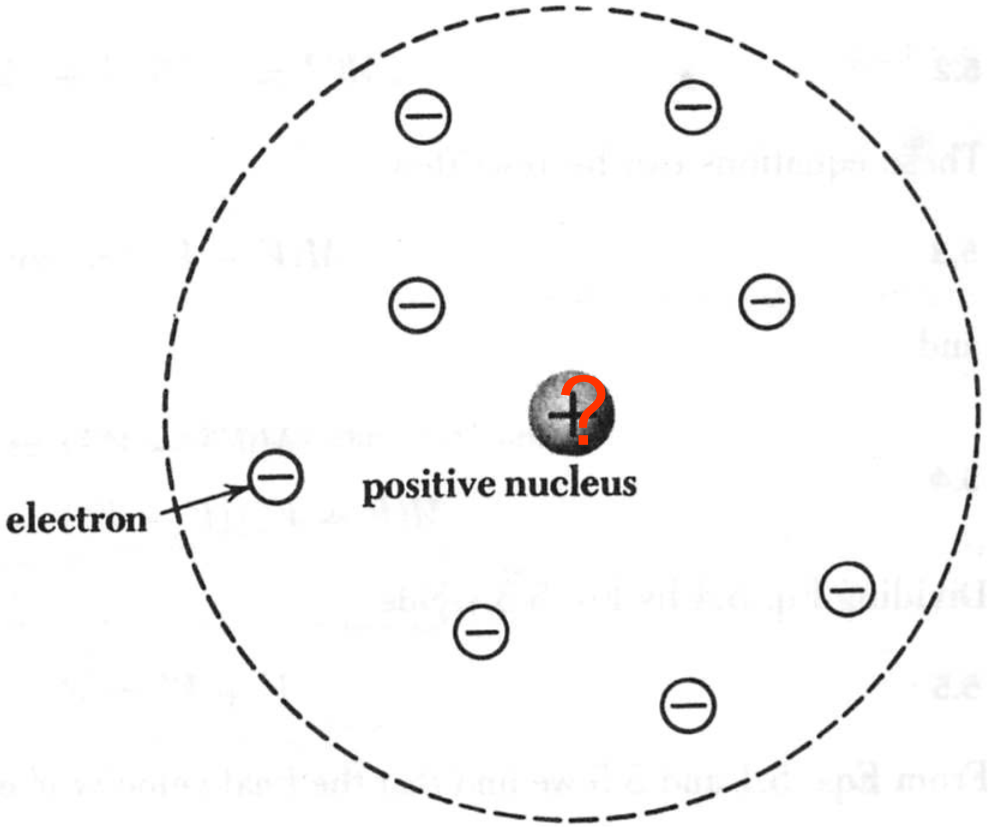




The number of particles scattered per unit area is:

$$N(\theta) = \frac{N_i n t}{16}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{Z_1^{\,2} Z_2^{\,2}}{r^2 K^2 \sin^4(\theta/2)}$$

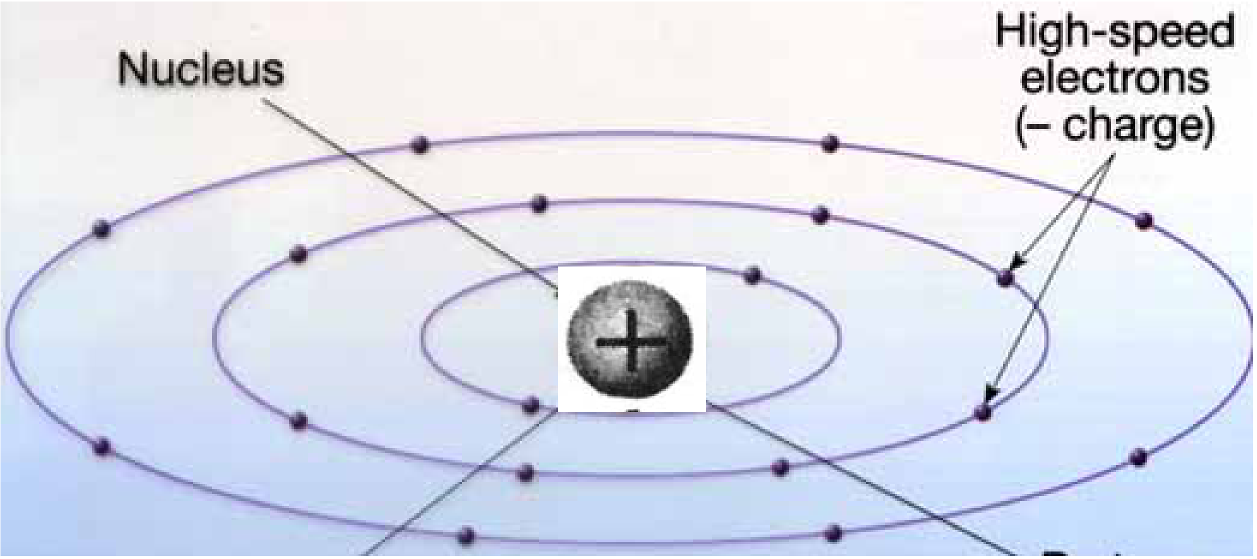
Structure of atom in 1911



What is a nucleus made of ?

What is its composition ?

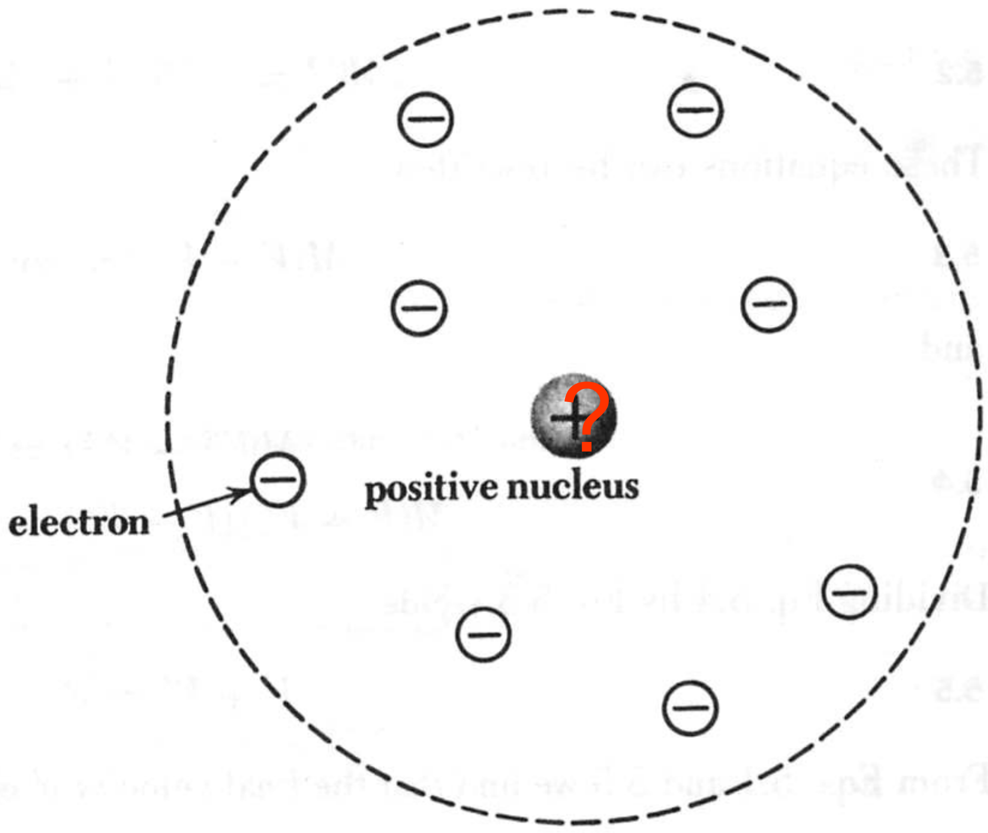
Planetary Model of the Atom (1915)



Niels Bohr (1885-1962)

- The Bohr Planetary Model of the Hydrogen Atom
- Atomic Excitation by Electrons
- Quantum mechanical treatment and the Shell model of Atom
- Spin of the electron (Stern Gerlach experiment)
- Closed shell & Magic numbers : 2, 8, 20, 28, 50 ……………
- Pauli exclusion principle for the electrons
- Characteristic X-Ray’s and Atomic Spectras, ……….

Knowledge of atoms in 1911

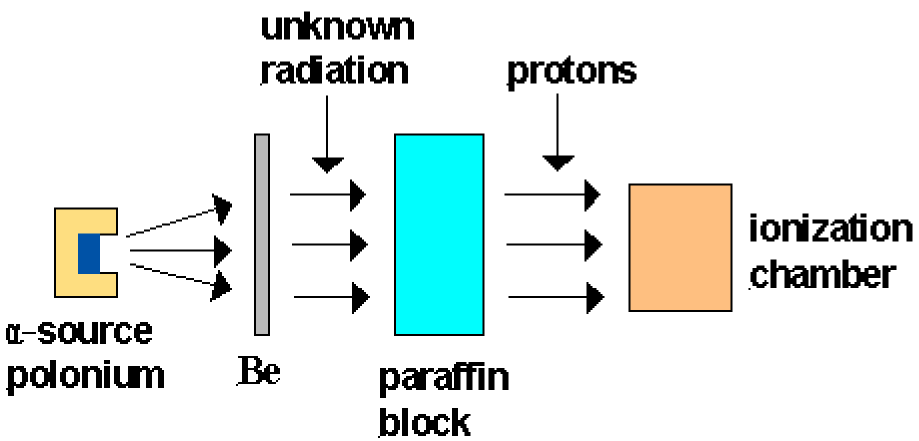


What is a nucleus made of ?

What is its composition ?

The discovery of neutron (1932)

In 1930, two German physicists, Bothe & Becker, bombarded the elements beryllium (Be) with alpha-particles. These elements, emitted a very penetrating form of radiation that was much more energetic than gamma-rays.



Schematic of the Joliots' Experiment

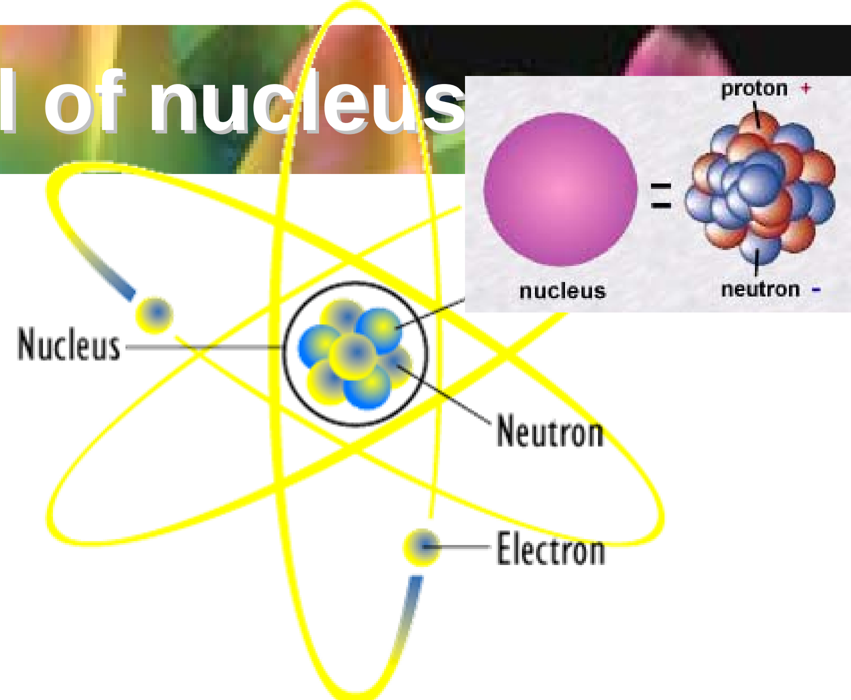
J. Chadwick proposed (1932) that the unknown radiation was a new type of particle – NEUTRON, it has to be charge neutral with roughly the same mass as proton

Chadwick explained the process occurring in the experiment as:

$$ {}^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n $$

neutron

The proton-neutron model of nucleus



- Following Chadwick's discovery of the neutron, a new model of the nucleus.

- The nucleus consists of **protons and neutrons**. Together they are called **nucleons**

- The **number of protons in the nucleus** is called the **atomic number** of the nucleus.

- The **total number of protons and neutrons in the nucleus** is called the **mass number** of the nucleus.

- Each nucleus can be represented as $^{A}_{Z}X$

where x = element symbol (eg Na, Co, U), Z = atomic number and A = mass number.

The **proton-neutron model** of the nucleus is still the basic model used today.

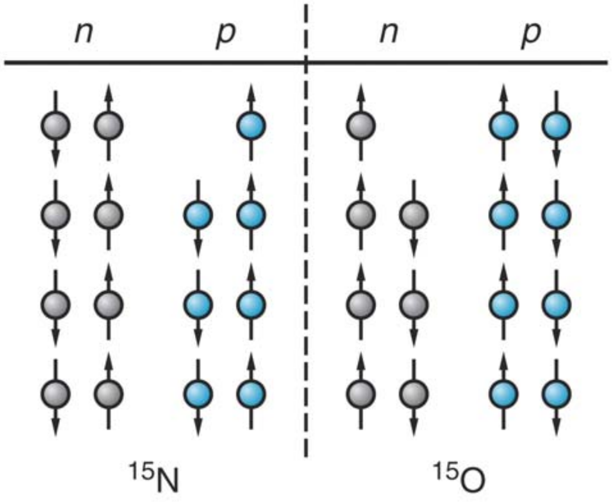
Few Nuclear Terminology

- Nuclides with the same Z are called isotopes. They have the same chemical properties.

- Nuclides with the same N are called isotones.

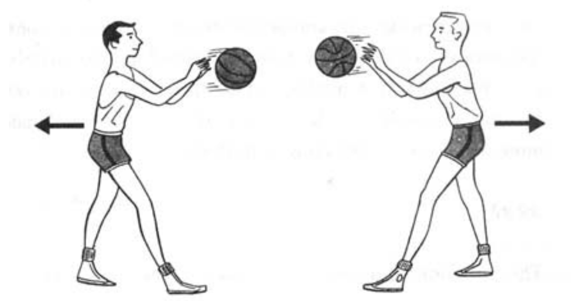
- Nuclides with the same A are called isobars and have approximately the same mass.

- Nuclides with N and Z interchanged are called mirror nuclides.

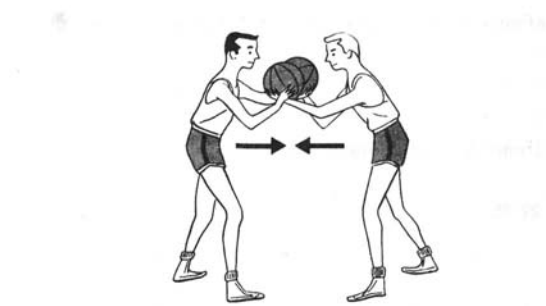


What holds the nucleons together ? There must be some force to hold them together in a nucleus

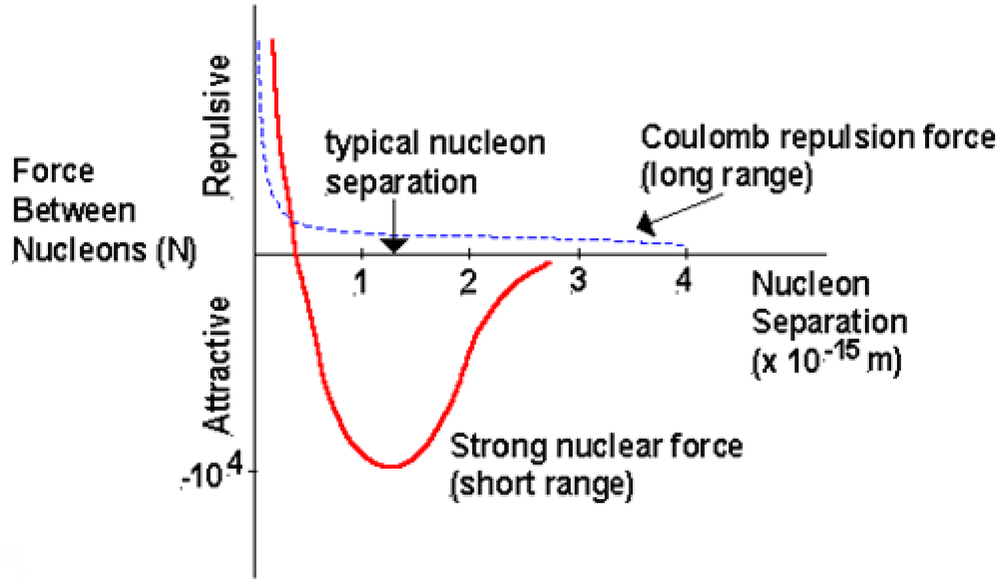
The force responsible for holding all nucleons together is the strong <u>nuclear force</u> (H. Yukawa, 1934)



repulsive force due to particle exchange



attractive force due to particle exchange



Yukawa's theory of meson exchange

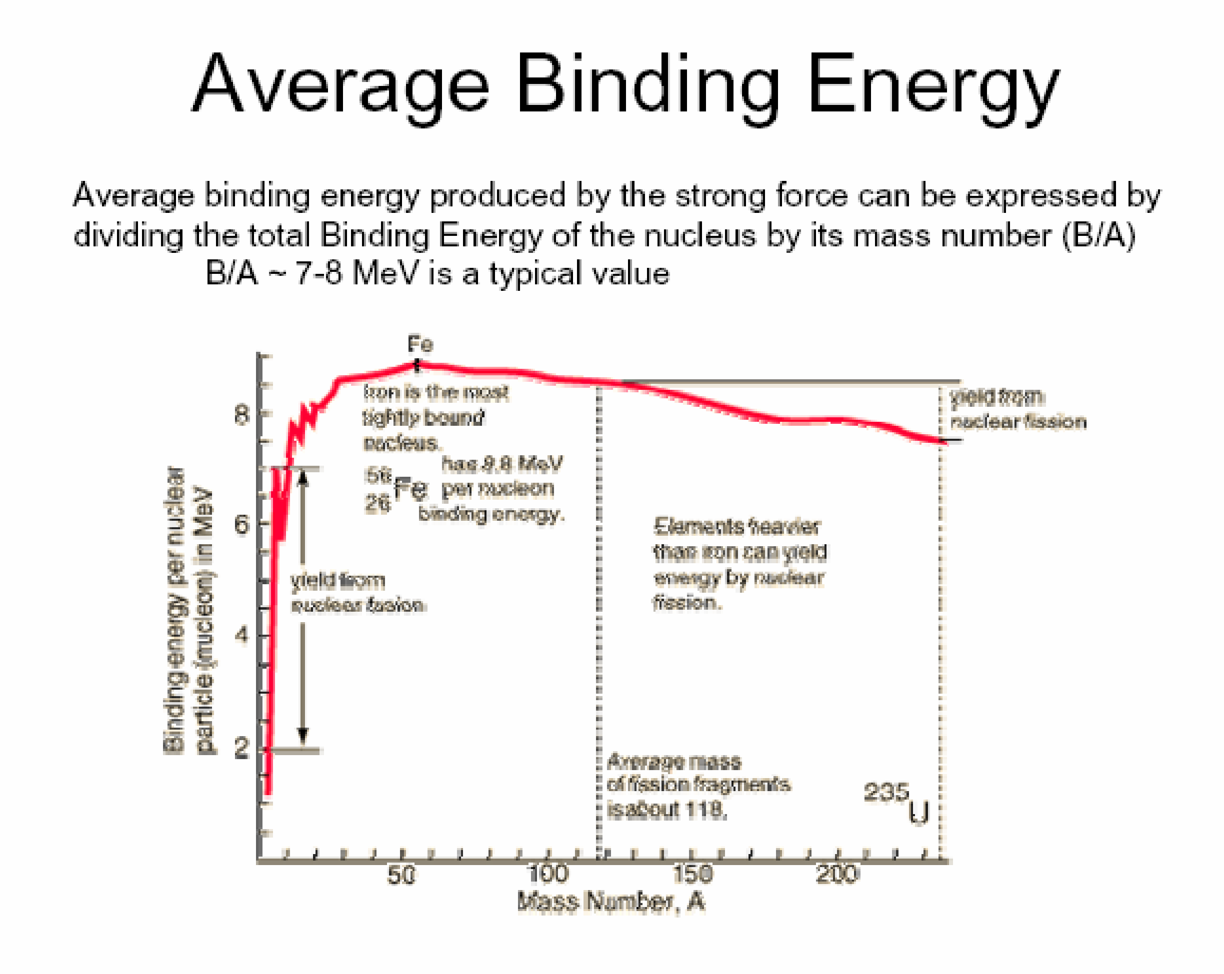
Binding energy of a nucleus

$$B = (Z\,M_p + N\,M_n - M)C^2$$

It is the energy required to break a nucleus into its constituent nucleons

It determines the stability of the nucleus

Larger the binding energy, more difficult it is to break a nucleus into its separate constituents



Semi-emperical Binding energy formula (Weiszsacher, 1935)

The Liquid Drop Model (I)

- Goal: estimate the binding energy of a given nucleus with a “semi-empirical” model.
  - Nucleus = Collection of interacting particles in a liquid drop of nuclear matter

Symmetry term: in the absence of the Coulomb force, the nucleus prefers to have N ≈ Z

$$B\left({}_{Z}^{A}X\right) = a_V A - a_A A^{2/3} - \frac{3}{5}\frac{Z(Z-1)e^2}{4\pi\varepsilon_0 r} - a_S \frac{(N-Z)^2}{A} + \delta$$

Volume term: The binding energy is approximately the sum of all the interactions between the nucleons.

Surface term: Correction for the nucleons at the surface of the nucleus (interact with less neighbors)

Coulomb term: Adding more protons increases the Coulomb repulsion within the nucleus

Pairing term

The Liquid Drop Model (II)

$$B\left({}^{A}_{Z}X\right) = a_V A - a_A A^{2/3} - \frac{3}{5}\frac{Z(Z-1)e^2}{4\pi\varepsilon_0 r} - a_S\frac{(N-Z)^2}{A} + \delta$$

$a_V = 14$ MeV Volume

$a_A = 13$ MeV Surface

$a_S = 19$ MeV Symmetry

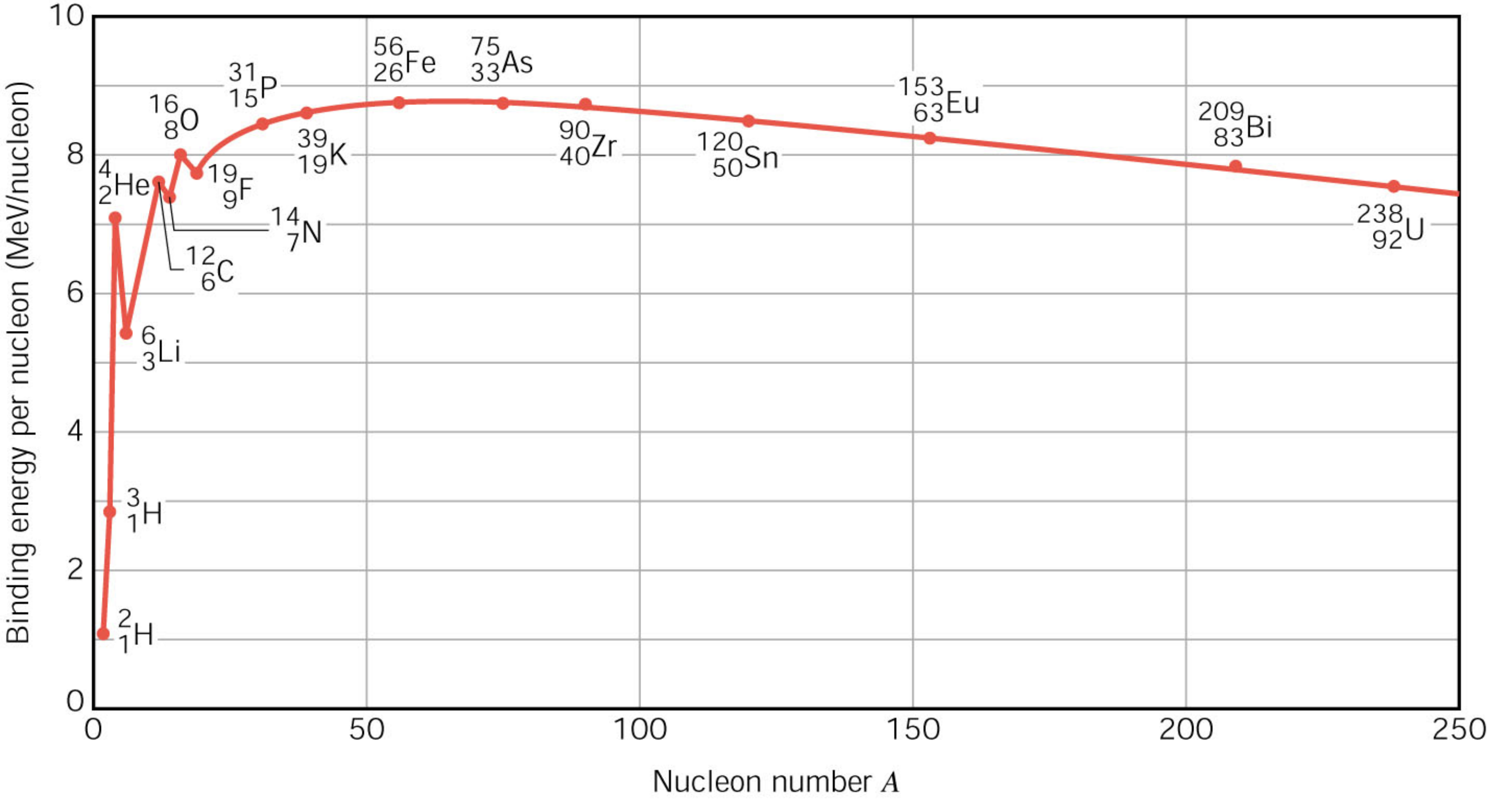
One can show that the Coulomb term can also be written (See example 12.5 p436):

$E_c = 0.72\, Z(Z-1)\, A^{-1/3}$ MeV

$$\text{Pairing } \delta = \begin{cases} +\Delta & \text{for even-even nuclei} \\ 0 & \text{for odd-}A\text{ (even-odd, odd-even) nuclei} \\ -\Delta & \text{for odd-odd nuclei} \end{cases}$$

With $\Delta = 33\, A^{-3/4}$ MeV

Liquid drop model cannot explain the fine structures in the Binding energy curves



Peaks appear in binding energy curve for nucleus with magic numbers of protons and/or neutrons, just like in electronic structure of electrons

Evidence for shell structure in the nucleus

The Shell Model of Nucleus (1933, 1948)

Bartlett *et al* propose shell model, similar to that used to study electronic structure of atom, for the nucleus (1933)

Could explain only the first 3 magic numbers 2, 8, 10

All efforts to explain the nucleus using shell model abandoned

1948, M. Mayer, and independently Haxel, Jensen & Suess revived the Shell model of nucleus

Growing evidence from experimental data for a shell like structure of atomic nucleus

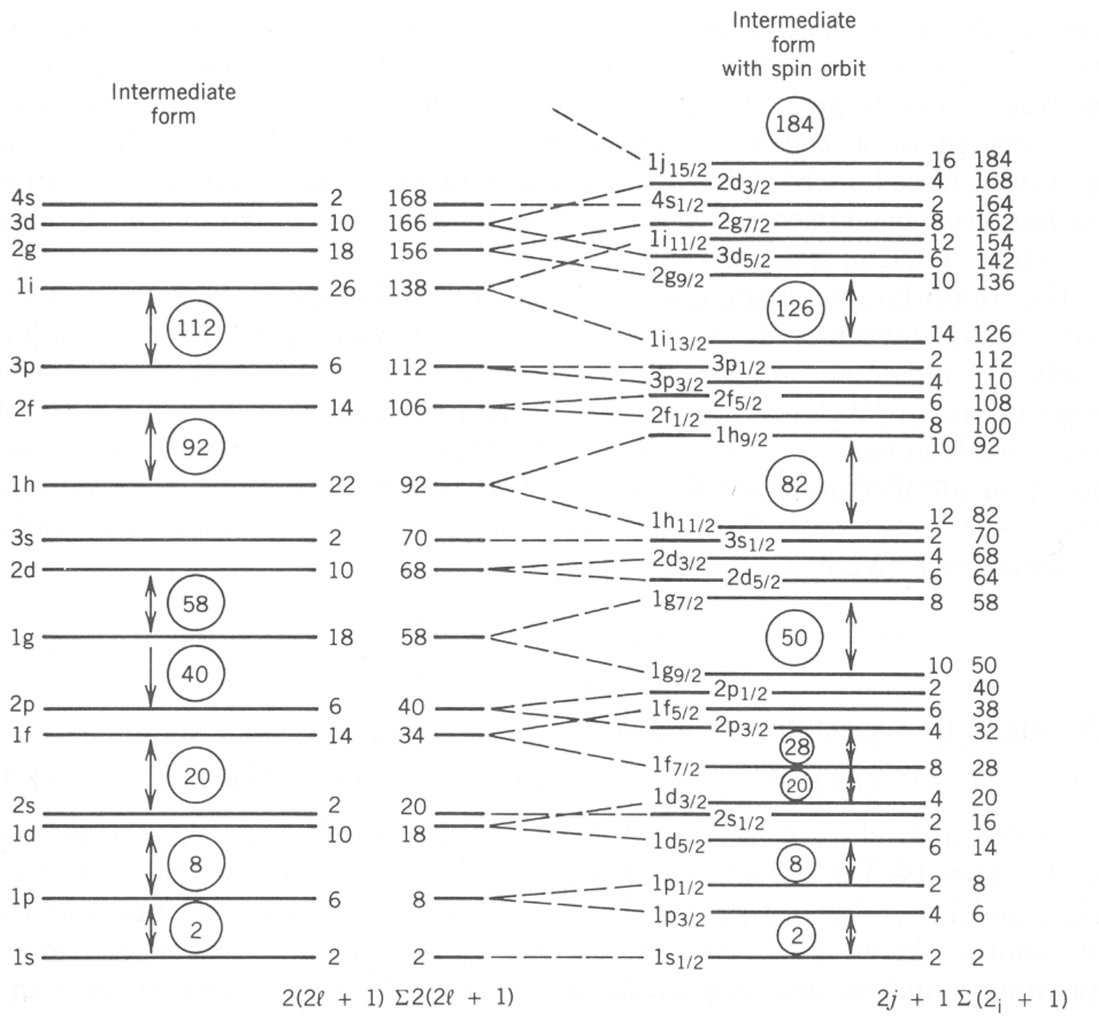
Spin-orbit coupling introduced

Could explain all the magic numbers

Maria Goppert-Mayer (1906-1972)

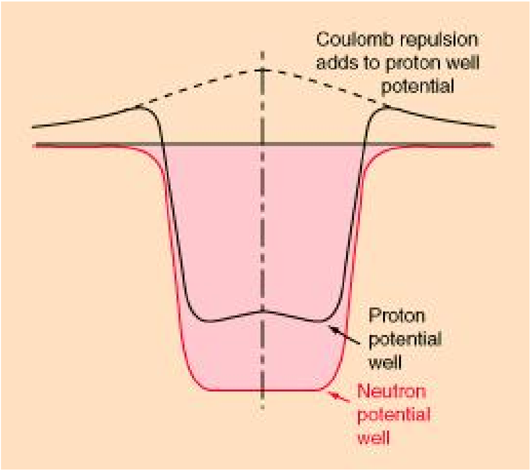
Spin-orbit coupling occurs when two motions are coupled together, such as the earth spinning on its axis as it orbits the sun. In an atom, the electron spins on an axis as it orbits the nucleus.

Shell Structure of the Nucleus



Nuclear energy levels

Each proton or neutron in the nucleus feels an average force from the other nucleons.
This force can be modeled as a potential well.



Shell Model of the Nucleus

- The various nucleons exist in certain energy levels within the nucleus,
- So-called magic numbers have been found:,2,8, 20, 50, 82, 126- isotopes containing these number of protons or neutrons have unusual stability in their structure.
- Nucleons can be excited to higher energy levels just like electrons. Gamma rays emitted.