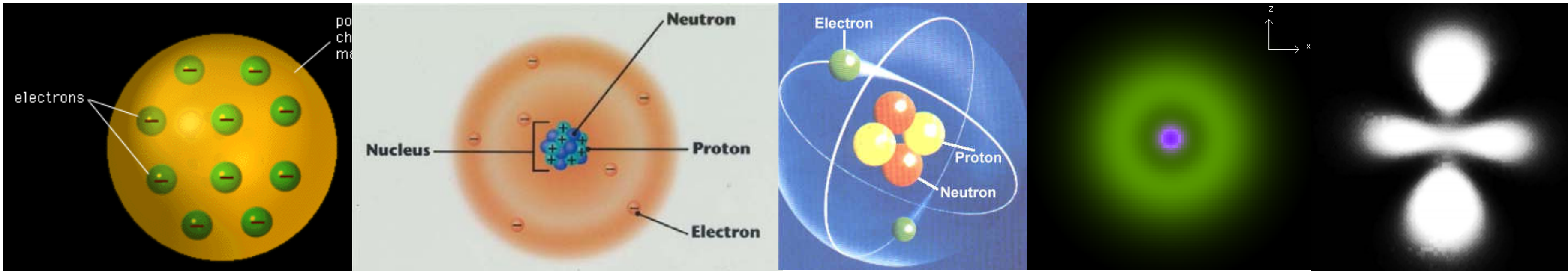


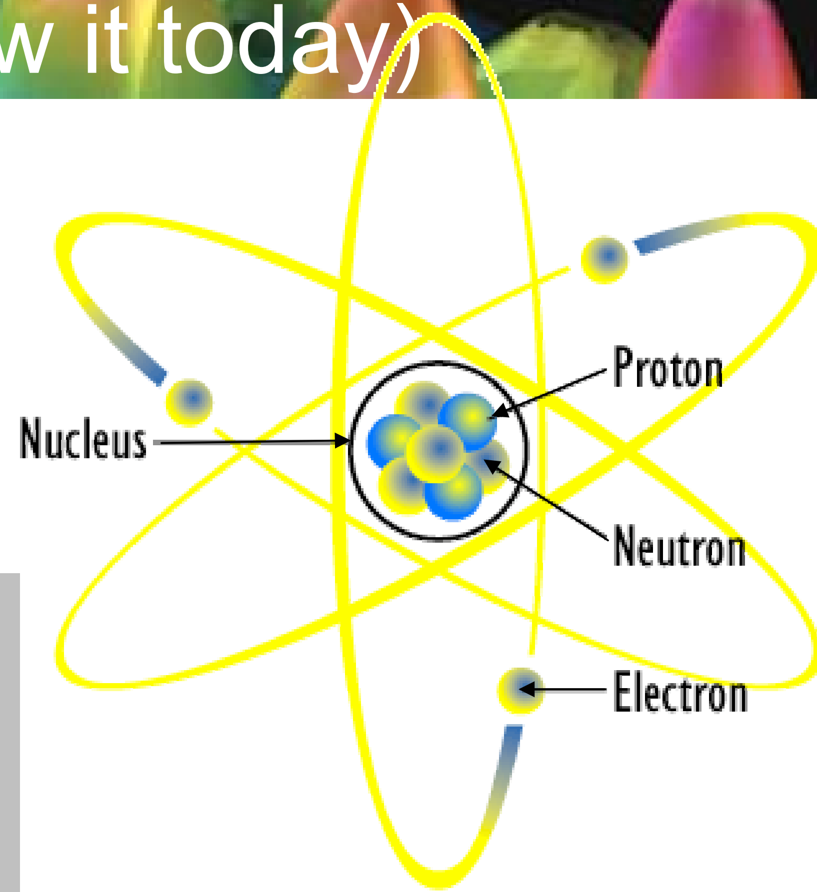

# Introduction to Nuclei – I
## (The Discovery)

*"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 Atom (as we know it today)

**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 |

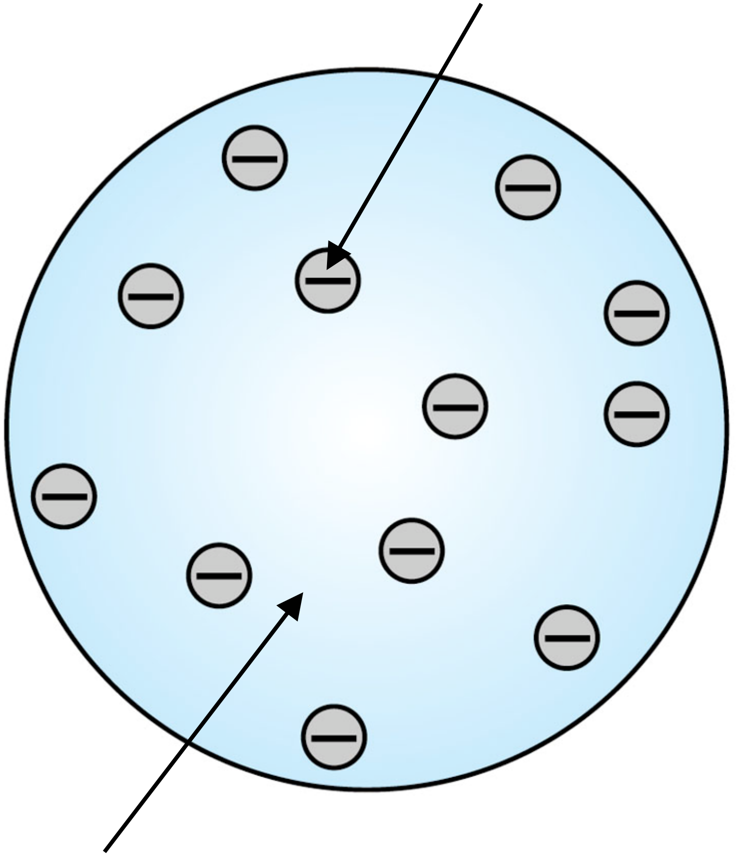
A heavy **NUCLEUS** with a POSITIVE electric charge surrounded by a swarm of much lighter particles, the NEGATIVELY charged **ELECTRONS**.

# Atom in 1900

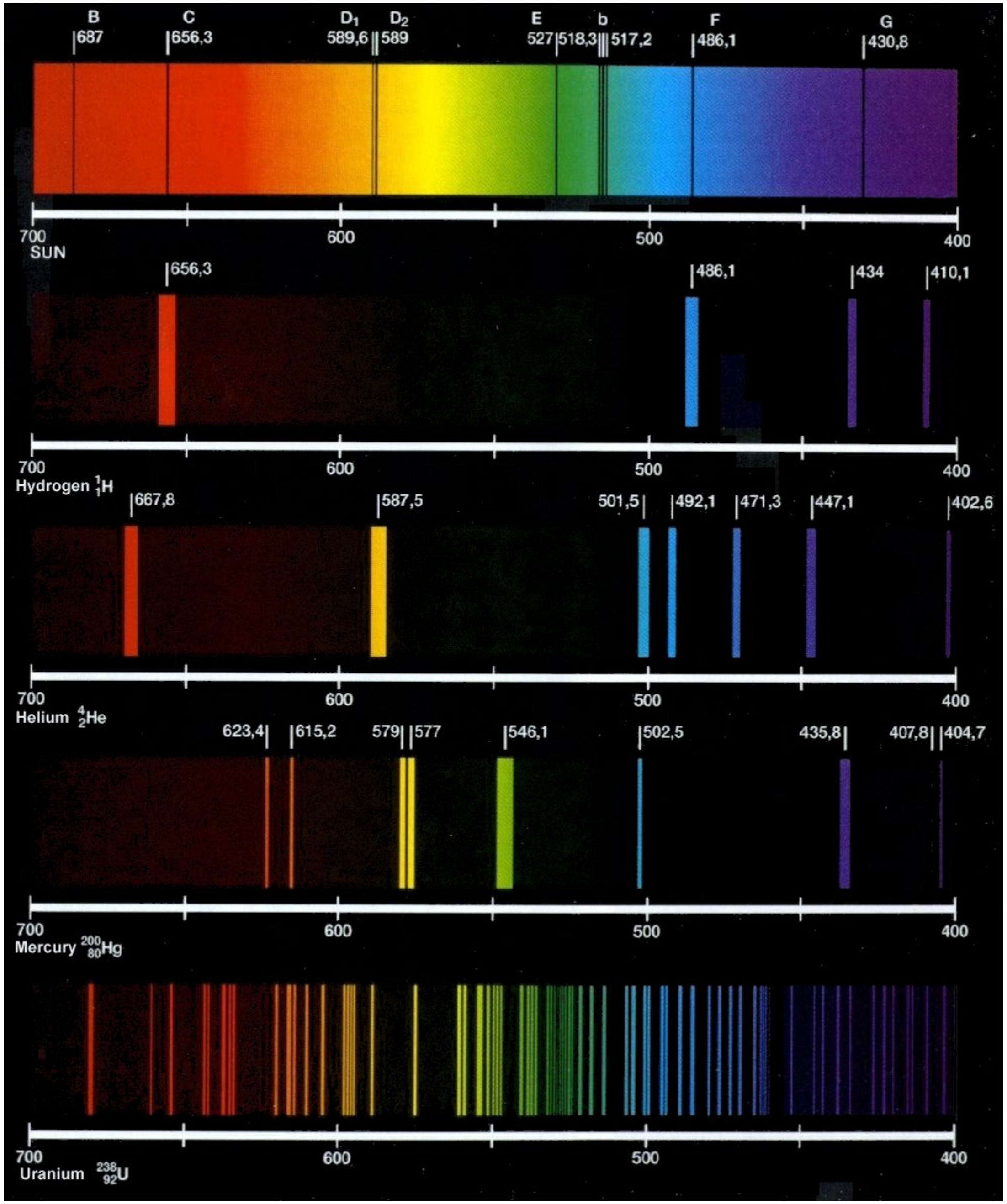
Amidst buzzing electricity and glowing tubes, J.J. Thomson discovered the electron (1897)

Proposes a model of Atom

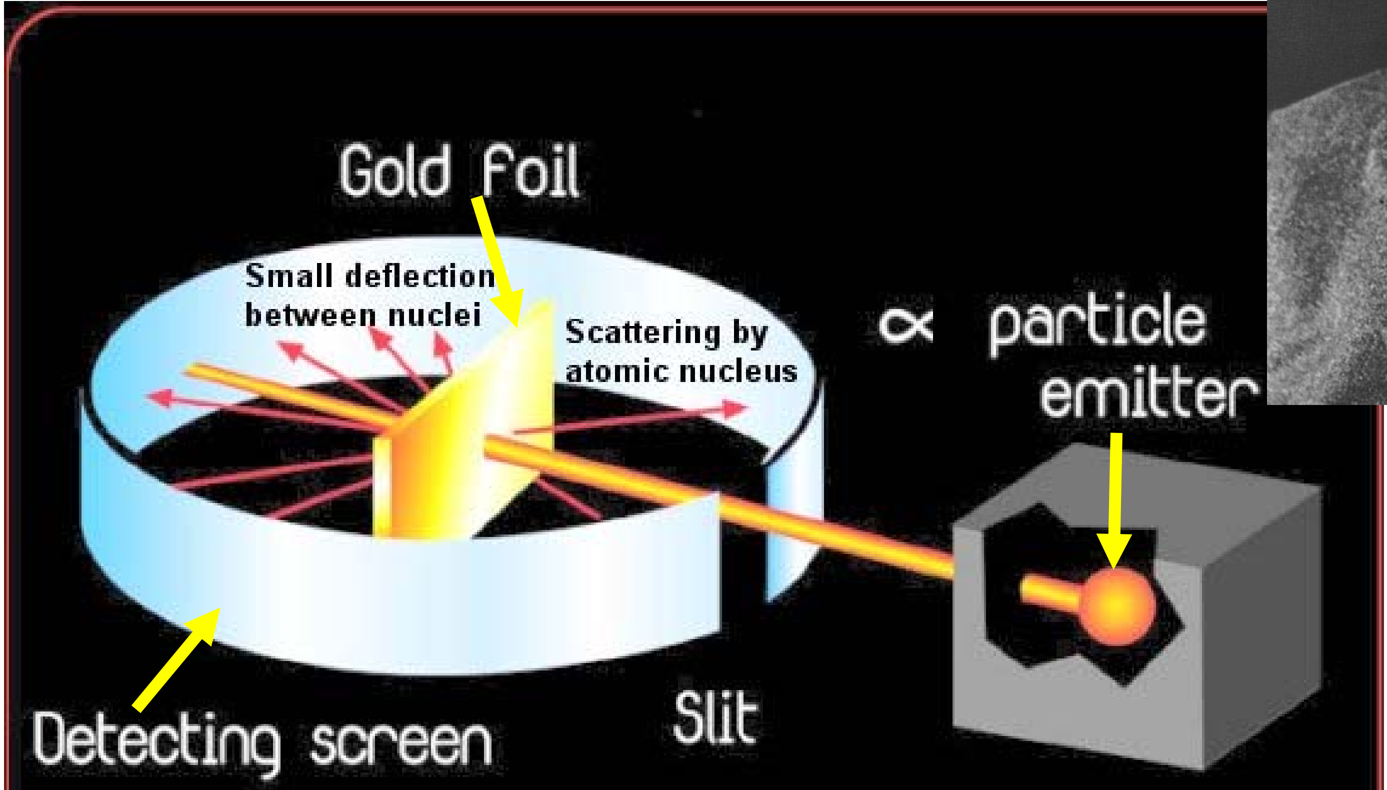
Thomson's "plum pudding" model



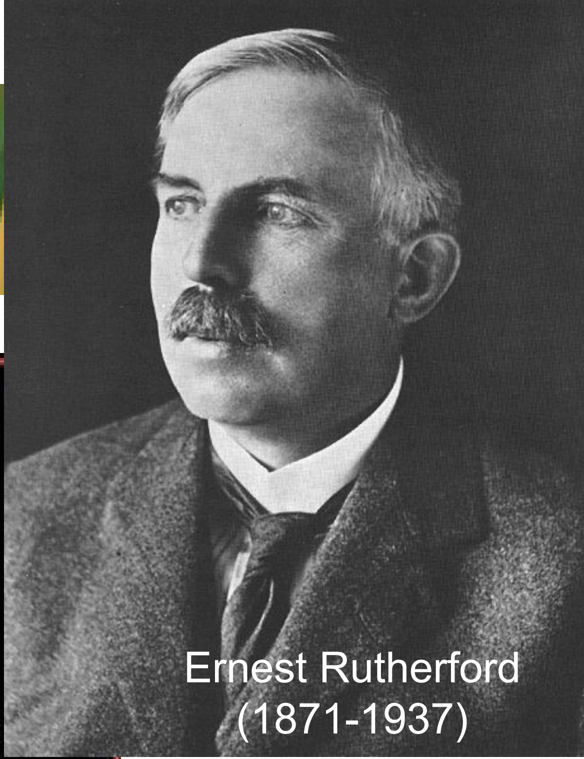
# Explaining the spectrum of light emitted from Atom – One of the most important problems of early $20^{th}$ Century Physics



# 1909, The α scattering experiment (The dawn of Nuclear Physics)



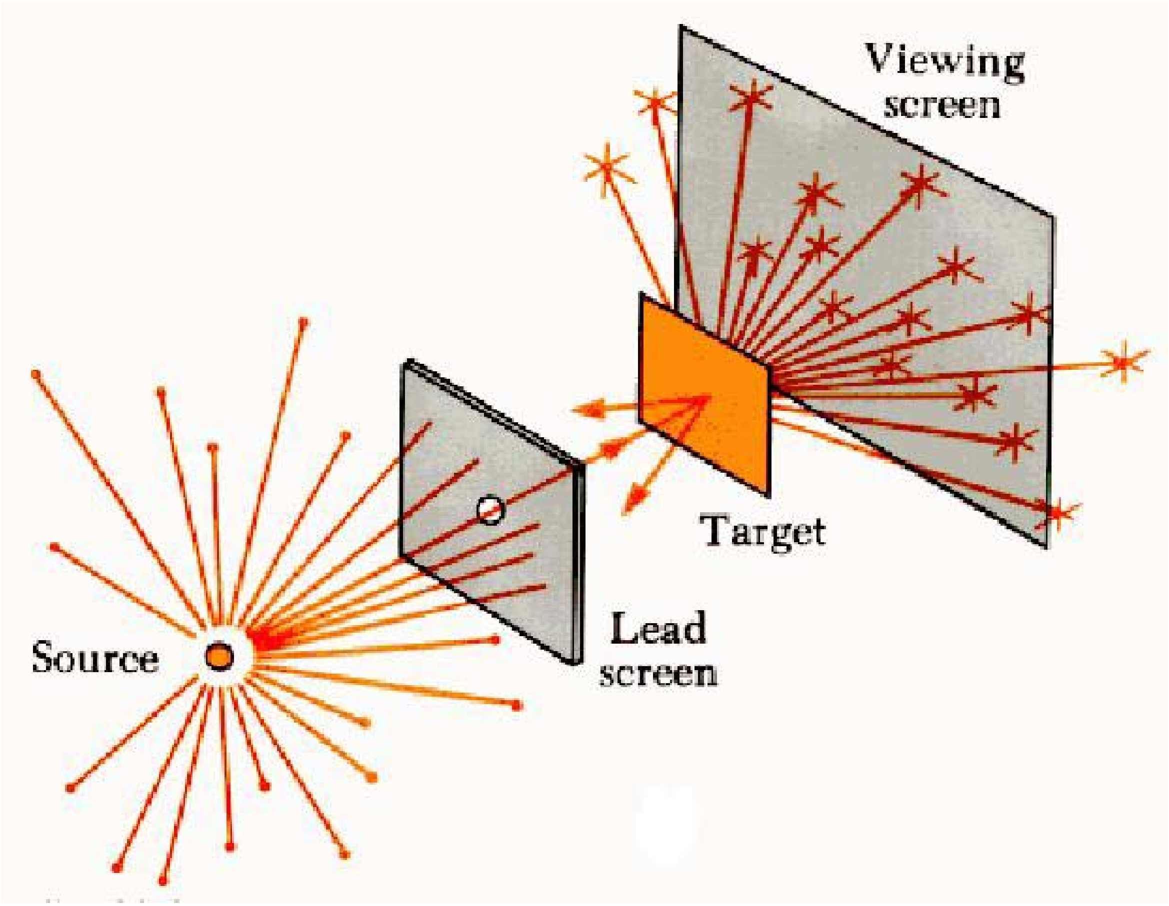

Geiger, and Marsden bombarded a thin gold foil with alpha particles (a helium atom with its electron stripped off).




Rutherford's Scattering Experiment (1909)

# Experiment of Geiger and Marsden (1909)

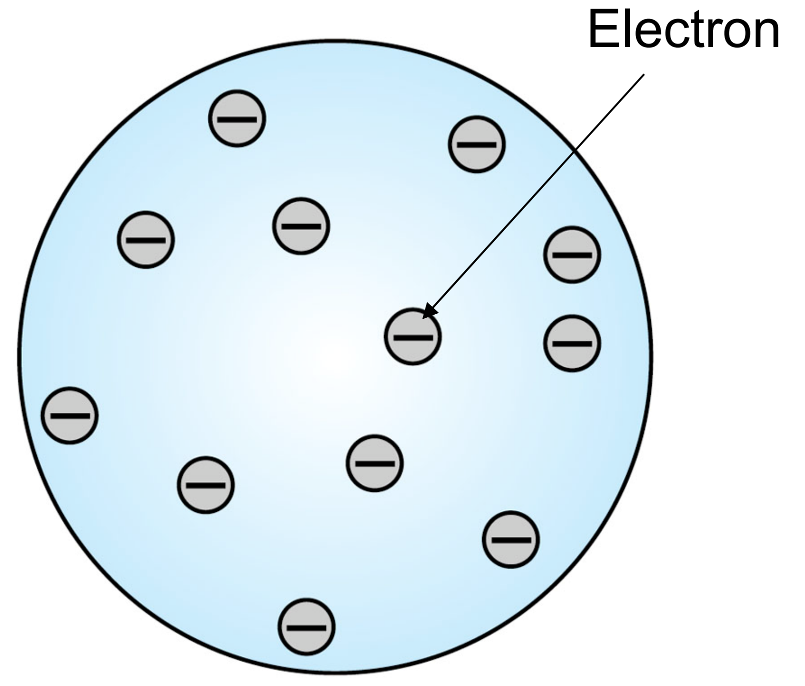
A good number of $\alpha$ particles were scattered from thin gold-leaf targets at backward angles (greater than 90°) !



*“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”*

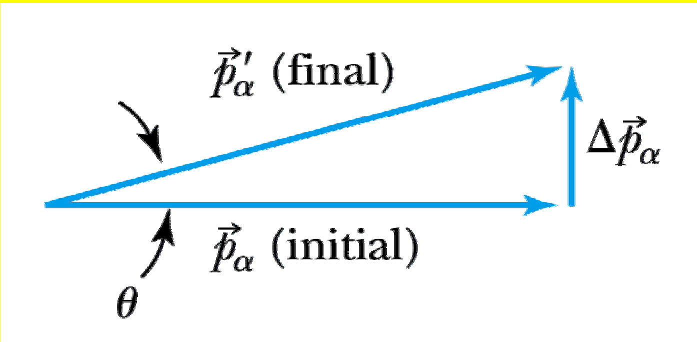
- E. Rutherford

What could have caused the α particles to scatter to such large angles ?




**Could it be the electrons ?**

Maximum scattering angle from electron — corresponding to the maximum momentum change.




$$\Delta p_{\max} = 2m_e v_\alpha$$

$$\theta_{\max} = \frac{\Delta p_\alpha}{p_\alpha} = \frac{2m_e v_\alpha}{M_\alpha v_\alpha} = 2.7\times10^{-4}\ \text{rad} = 0.016°$$

too small!

# Could it be the multiple scattering of electrons ?

If an $\alpha$ 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:

$$n = \frac{\text{Number of molecules}}{\text{cm}^3} = [\text{Avogadro's no. (molecules/mol)}]$$

$$\times \left[\frac{1}{\text{gram}-\text{molecular weight}}\left(\frac{\text{mol}}{\text{g}}\right)\right]\left[\text{density}\left(\frac{\text{g}}{\text{cm}^3}\right)\right]$$

$$= \left(6.02 \times 10^{23}\,\frac{\text{molecules}}{\text{mol}}\right)\left(\frac{1\text{ mol}}{197\text{ g}}\right)\left(19.3\,\frac{\text{g}}{\text{cm}^3}\right)$$

$$= 5.9 \times 10^{22}\,\frac{\text{molecules}}{\text{cm}^3} = 5.9 \times 10^{28}\,\frac{\text{atoms}}{\text{m}^3}$$

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

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

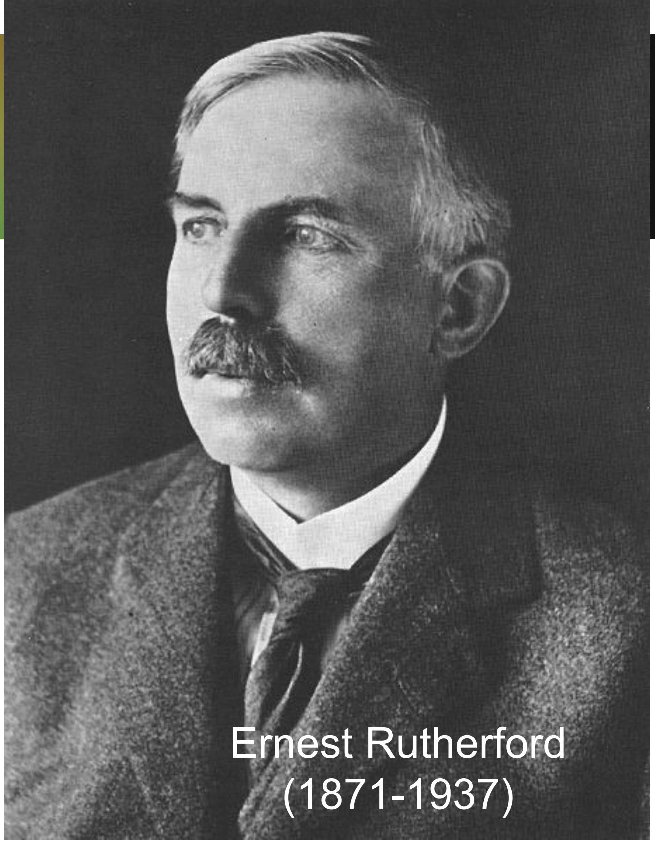
$$\langle\theta\rangle_{total} = \sqrt{2300}(0.016°) = 0.8°$$

still too small!

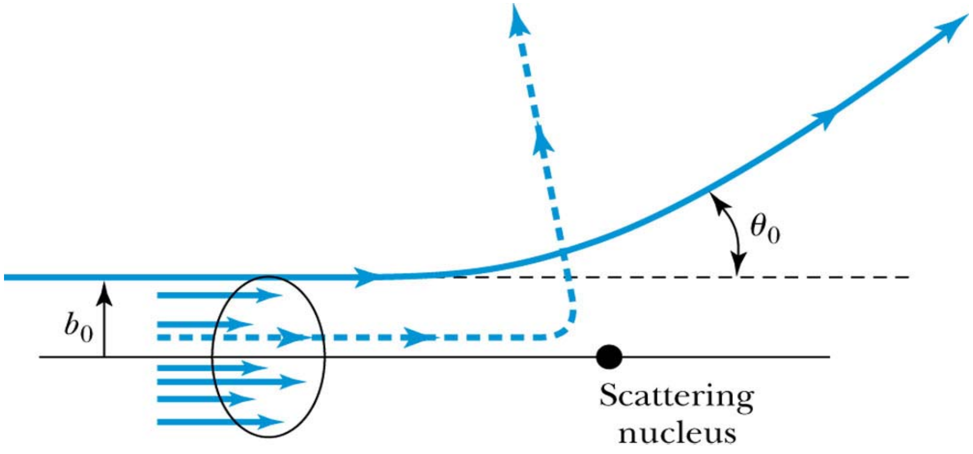
# 1911, Rutherford's Atomic Model (The Nucleus is born)

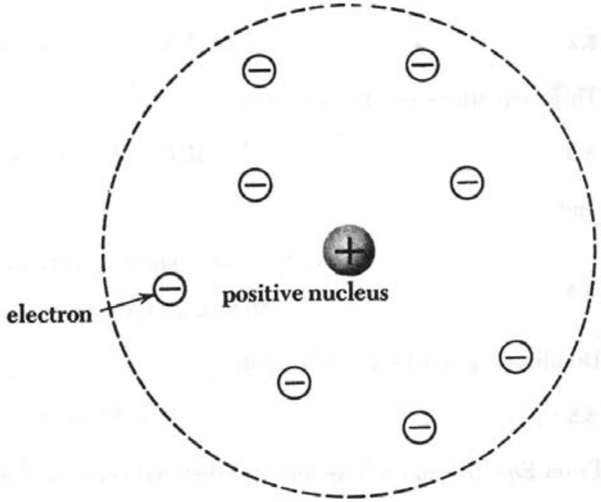
$\langle\theta\rangle_{total} = 6.8°$ even if the α particle is scattered from all 79 electrons in each atom of gold.

Atom should have a positively charged core (**nucleus**) surrounded by the negative electrons - Rutherford

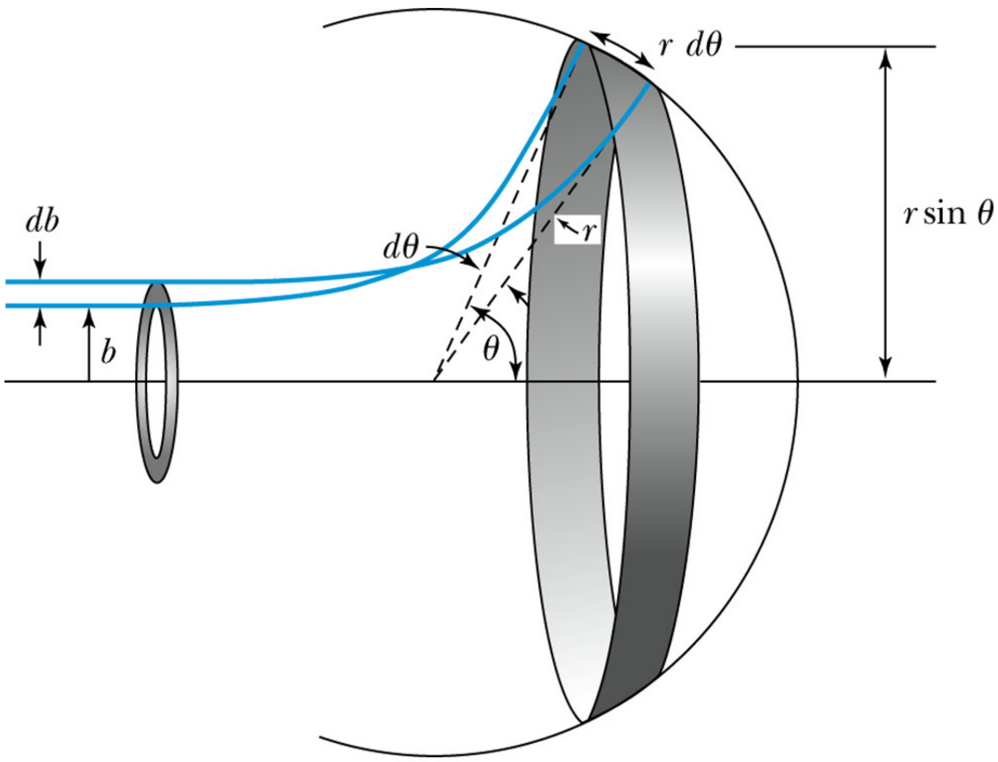


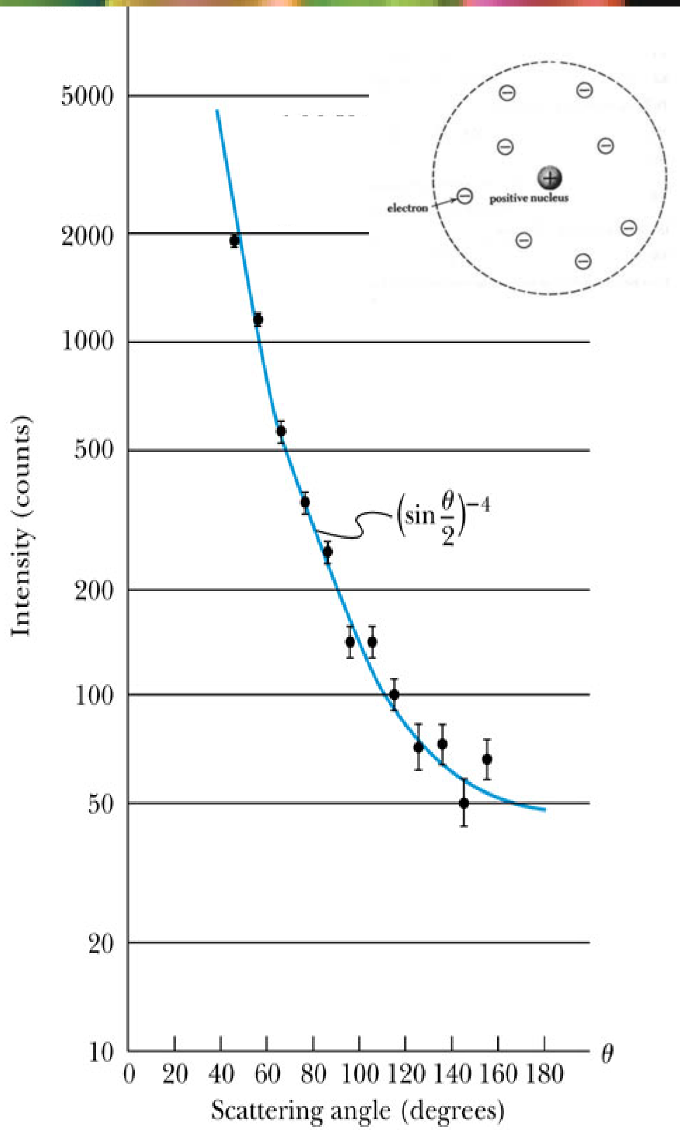
Ernest Rutherford (1871-1937)



# Rutherford's model can explain the experimental scattering data

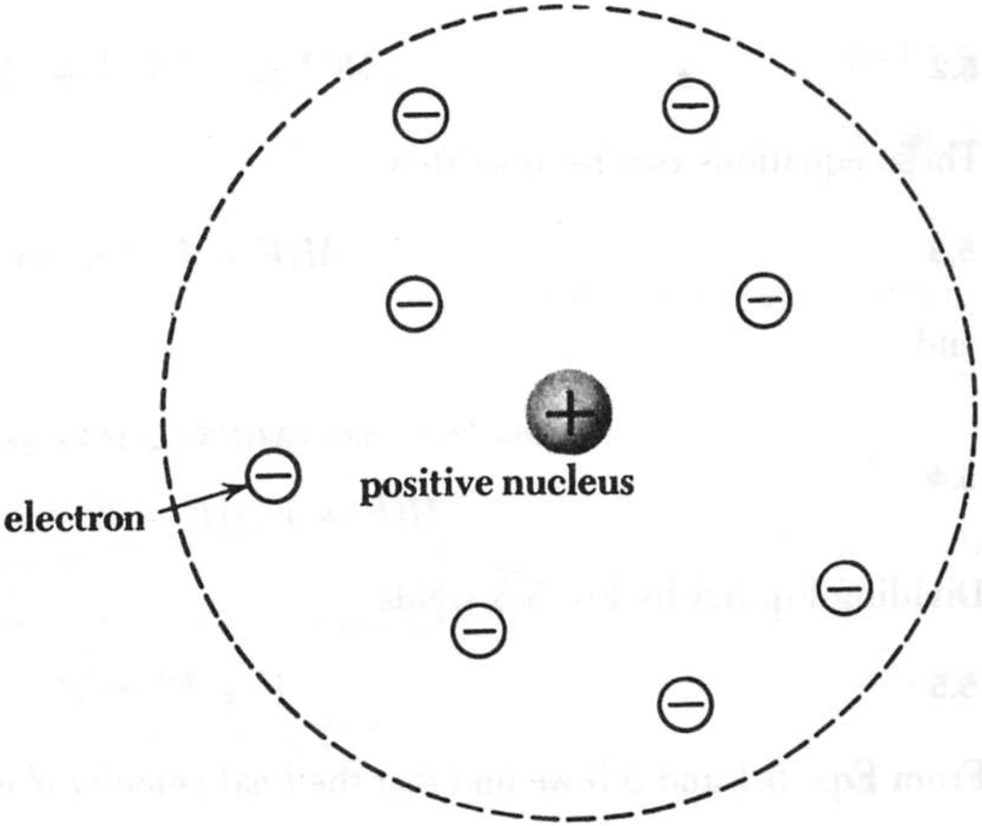



$$N(\theta) = \frac{N_i n t}{16}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{Z_1{}^2 Z_2{}^2}{r^2 K^2 \sin^4(\theta/2)}$$

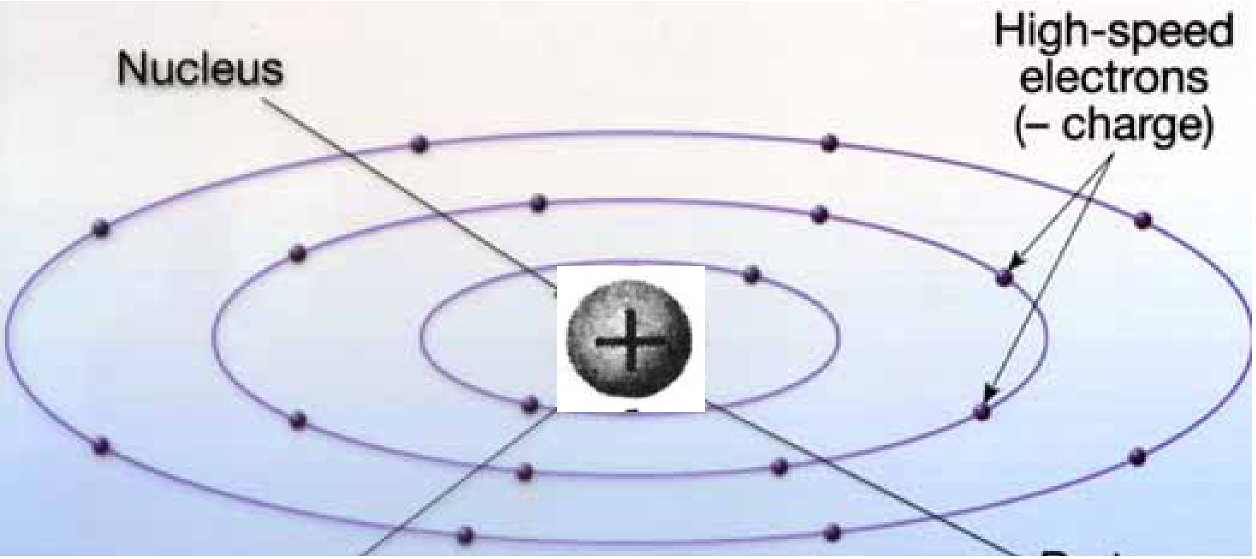
Rutherford's Scattering Formula

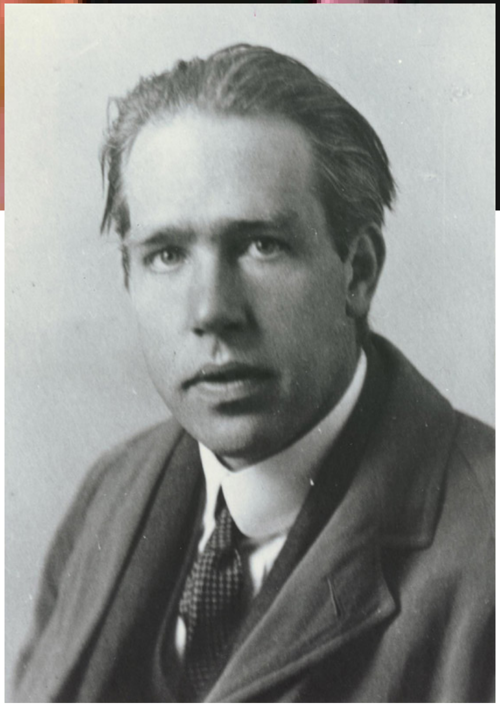
# Structure of Atom in 1911




A positively charged core **Nucleus** surrounded by **Electrons**.

# 1915, Bohr put Thomson's electron into orbit (Planetary Model of the Atom)

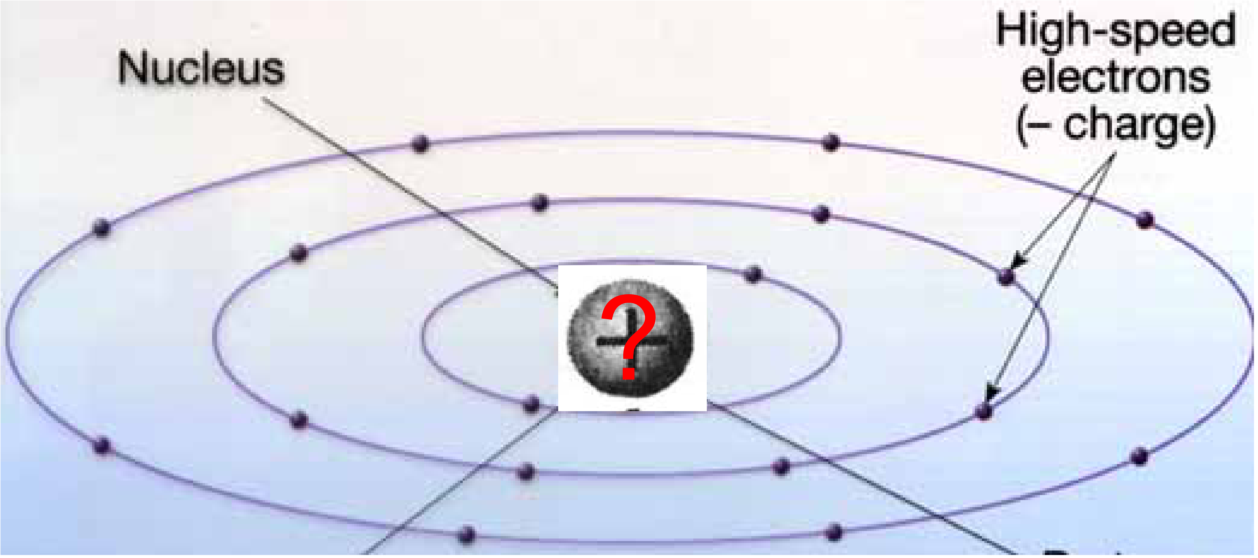


Niels Bohr (1885-1962)

- Bohr's Planetary Model could explain 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 Spectra, ……….

# Atomic Nucleus in 1915




What is the nucleus made of ?

What is its composition ?

# Proton is discovered (1918)
## (The philosopher's stone)

Alpha particle shot into Nitrogen gas.

Hydrogen nuclei detected in Scintillation detector.

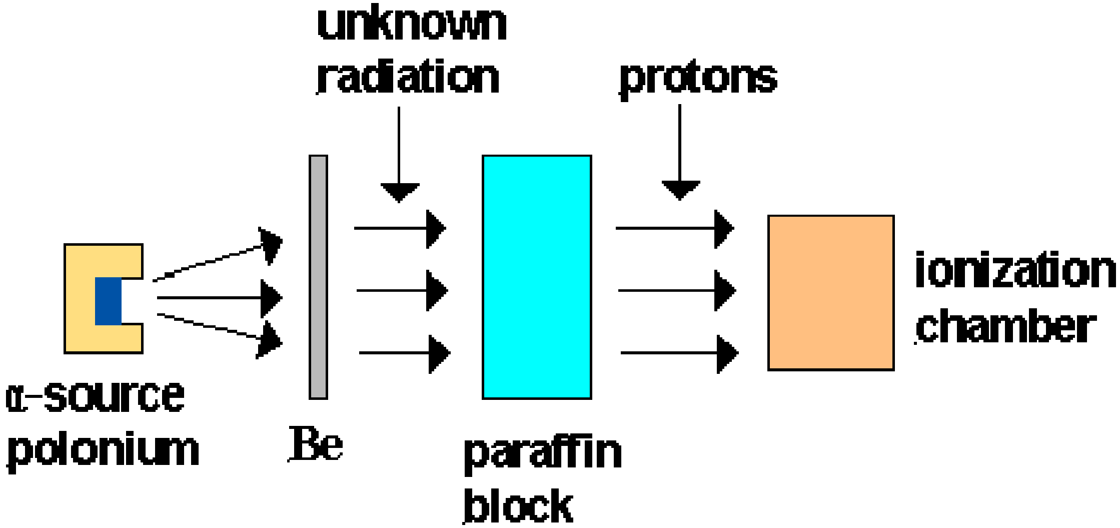
Rutherford concluded that Nitrogen must contain hydrogen nuclei.

Suggested that the hydrogen nucleus, which was known to have Atomic number of 1, was an elementary particle.

Called this particle as, "Proton".

# The discovery of Neutron (1932)
## (The last piece of the puzzle)

1930, Bothe & Becker, bombarded the element beryllium (Be) with alpha-particles. This reaction emitted a very penetrating neutral radiation. They thought it was gamma-rays.




Schematic of the Joliots' Experiment

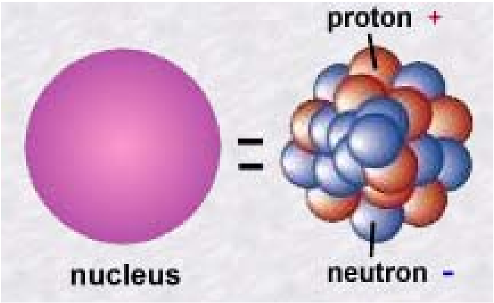
J. Chadwick proposed (1932) that the unknown radiation was a new type of particle – NEUTRON, - charge neutral & roughly the same mass as proton

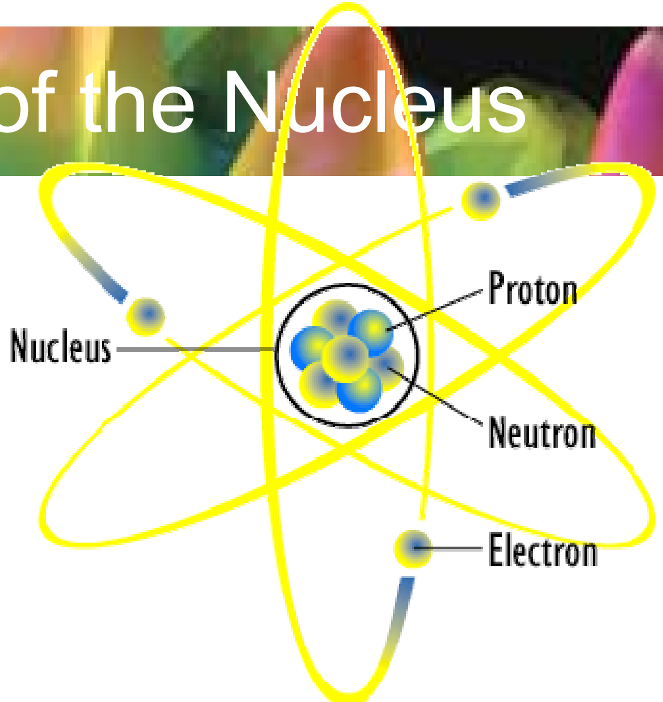
Chadwick explained the process occurring in the experiment as:

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

Neutron

# The proton-neutron model of the Nucleus




- The nucleus consists of **Protons and Neutrons**, together called **Nucleons.**

- The **number of Protons in the nucleus** is called the **Atomic number (Z)** of the nucleus.

- The **total number of Protons and Neutrons in the nucleus** is called the **Mass number (A)** of the nucleus.

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

where X = element symbol (e.g., Na, Co, U), Z = Atomic number and A = Mass number.

Is still the basic model of the atomic nucleus today.

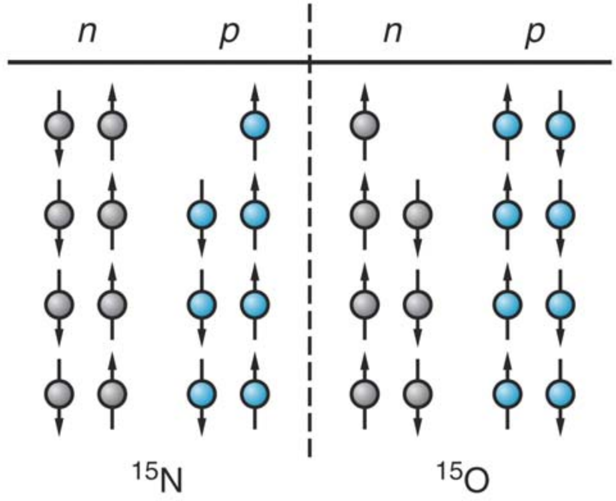
# Few Nuclear Terms

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

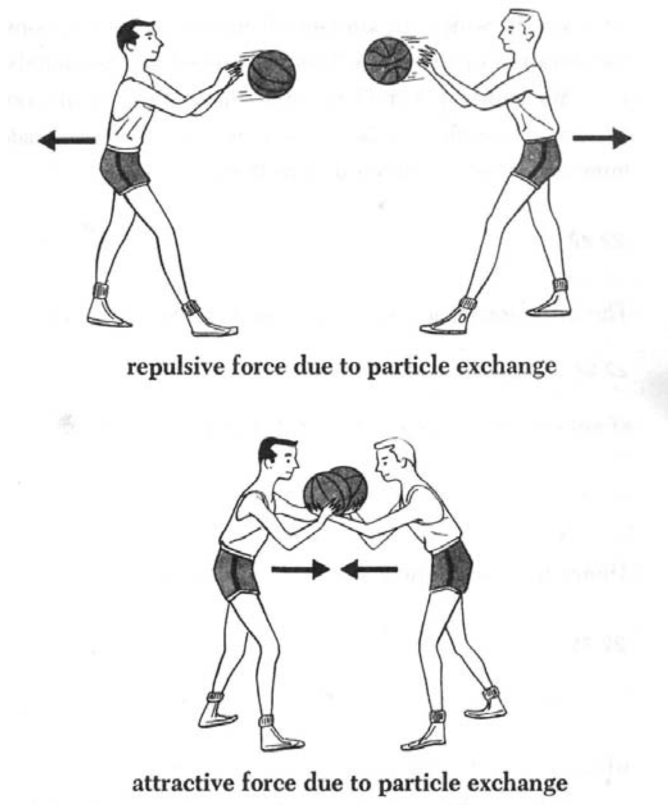
- Nuclides with the same N are called Isotones.

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

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

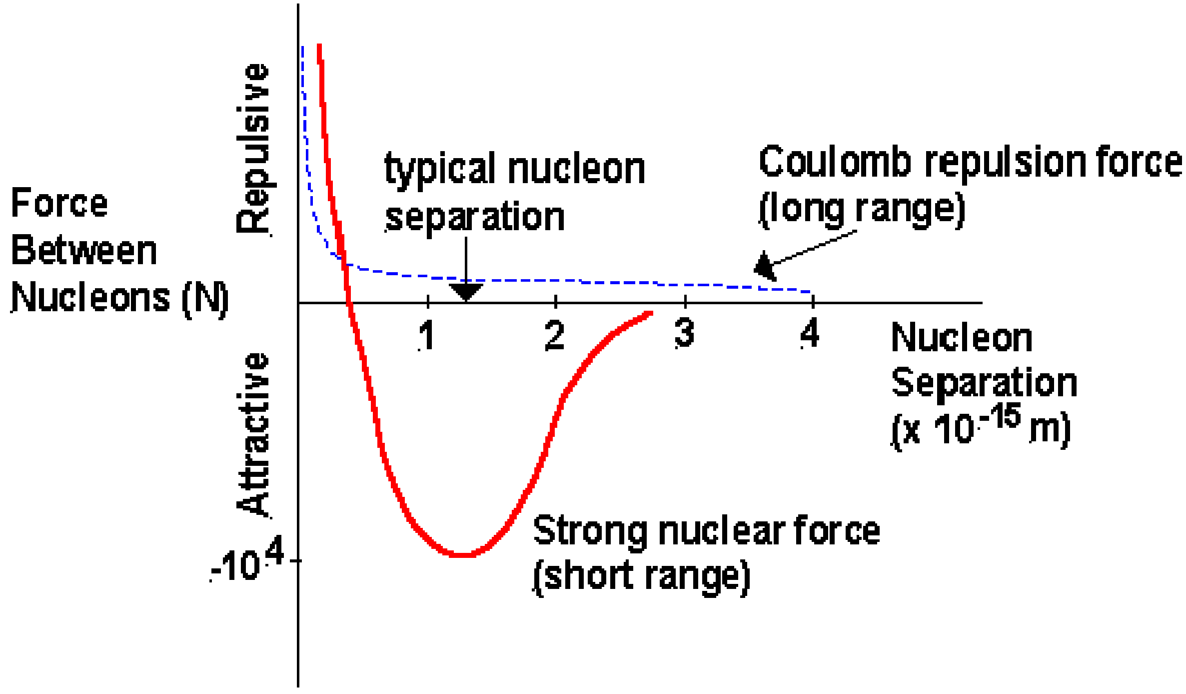


# What holds the nucleons in the nucleus together ?




Yukawa's theory of meson exchange, 1934

## The Nuclear Force

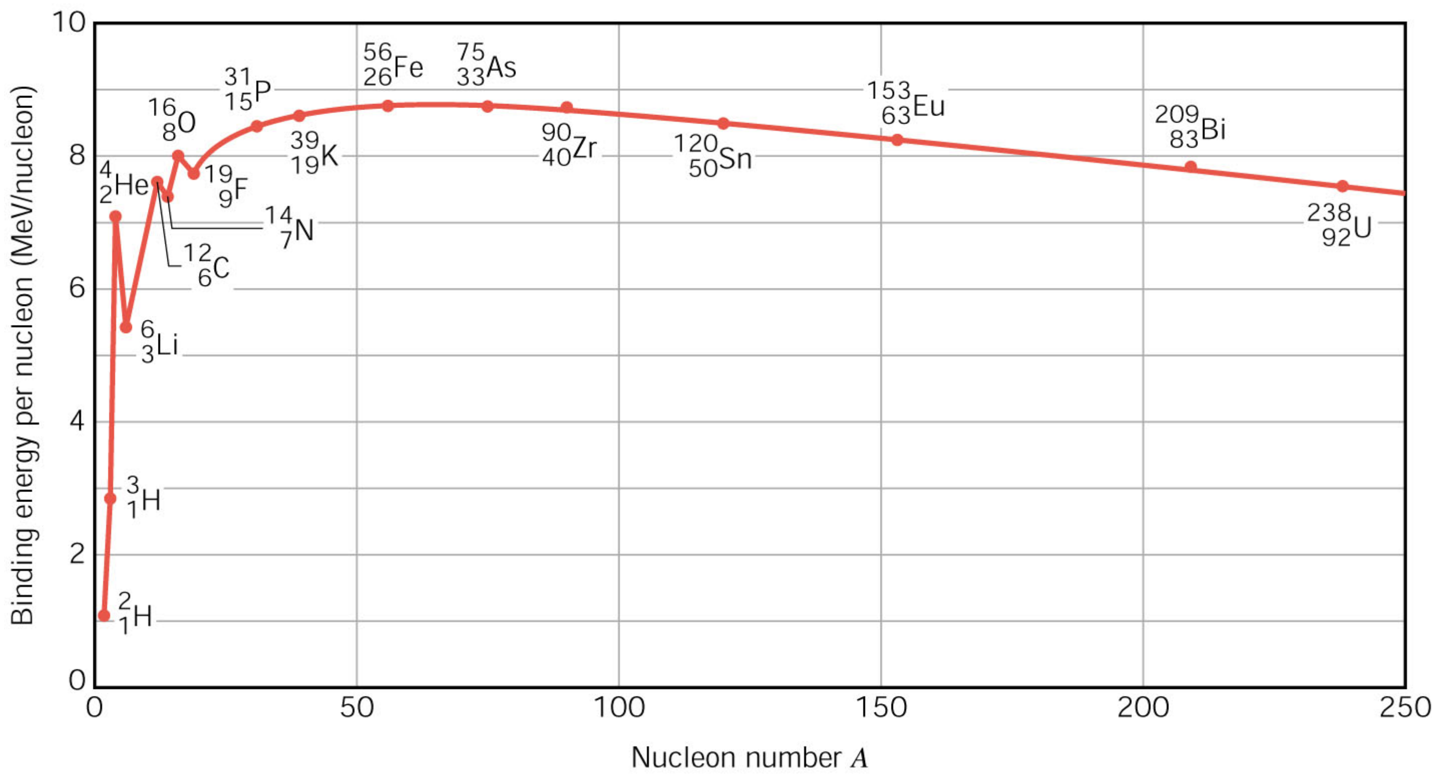


# Binding energy of the nucleus

Energy required to break the nucleus into its constituent nucleons.

$$B = (Z\,m_p + N\,m_n - M)c^2$$

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



# Semi-empirical Binding energy formula (V. 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

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

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 |

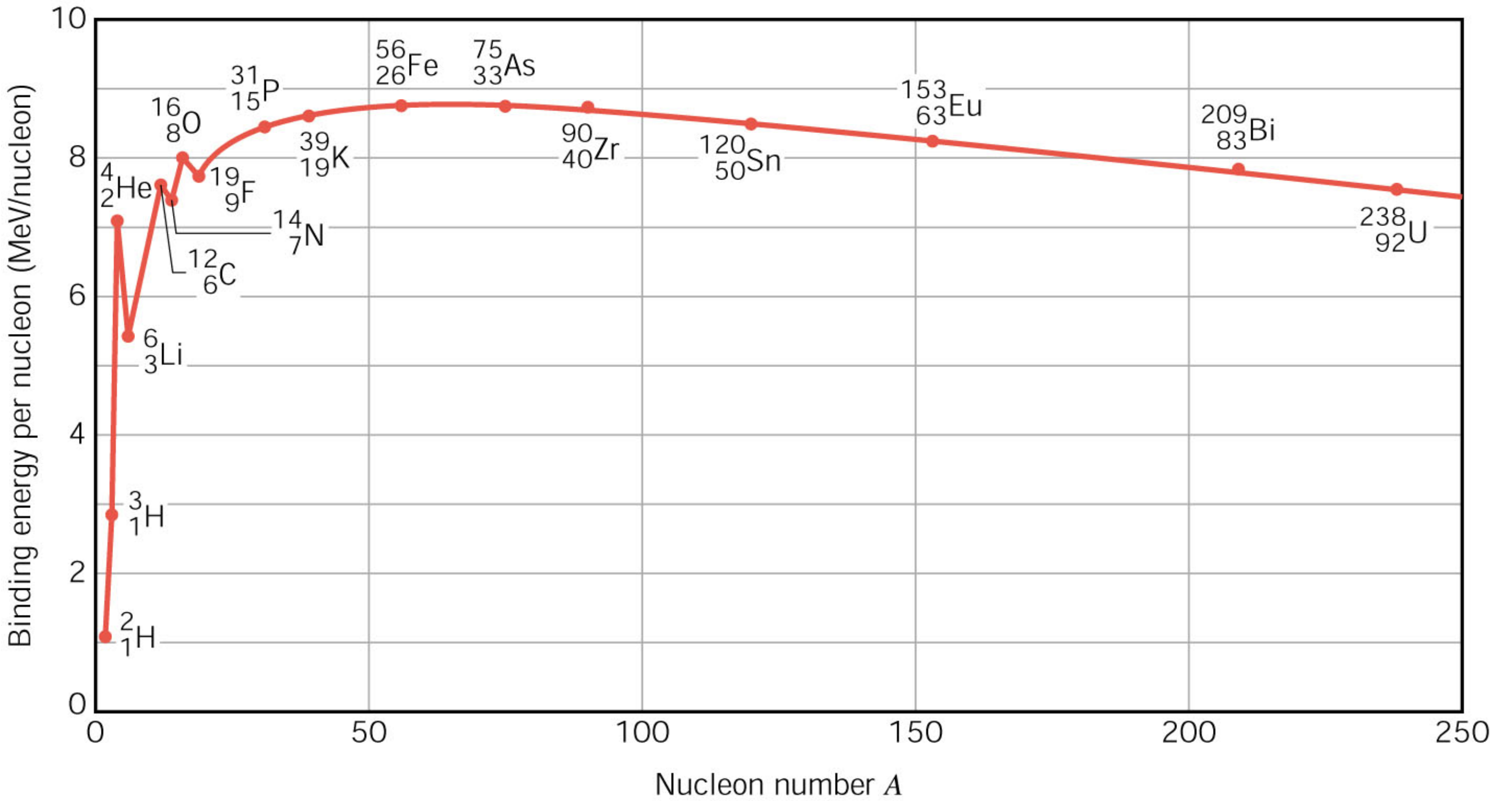
One can show that the Coulomb term can also be written (See example 12.5 p436):

$E_c = 0.72\ Z(Z-1)\ A^{-1/3}$ 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 the Nucleus (1933, 1948)

Similar to that used in the electronic structure of atom (Bartlett et al, 1933)

Could explain only the first 3 magic numbers 2, 8, 20

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

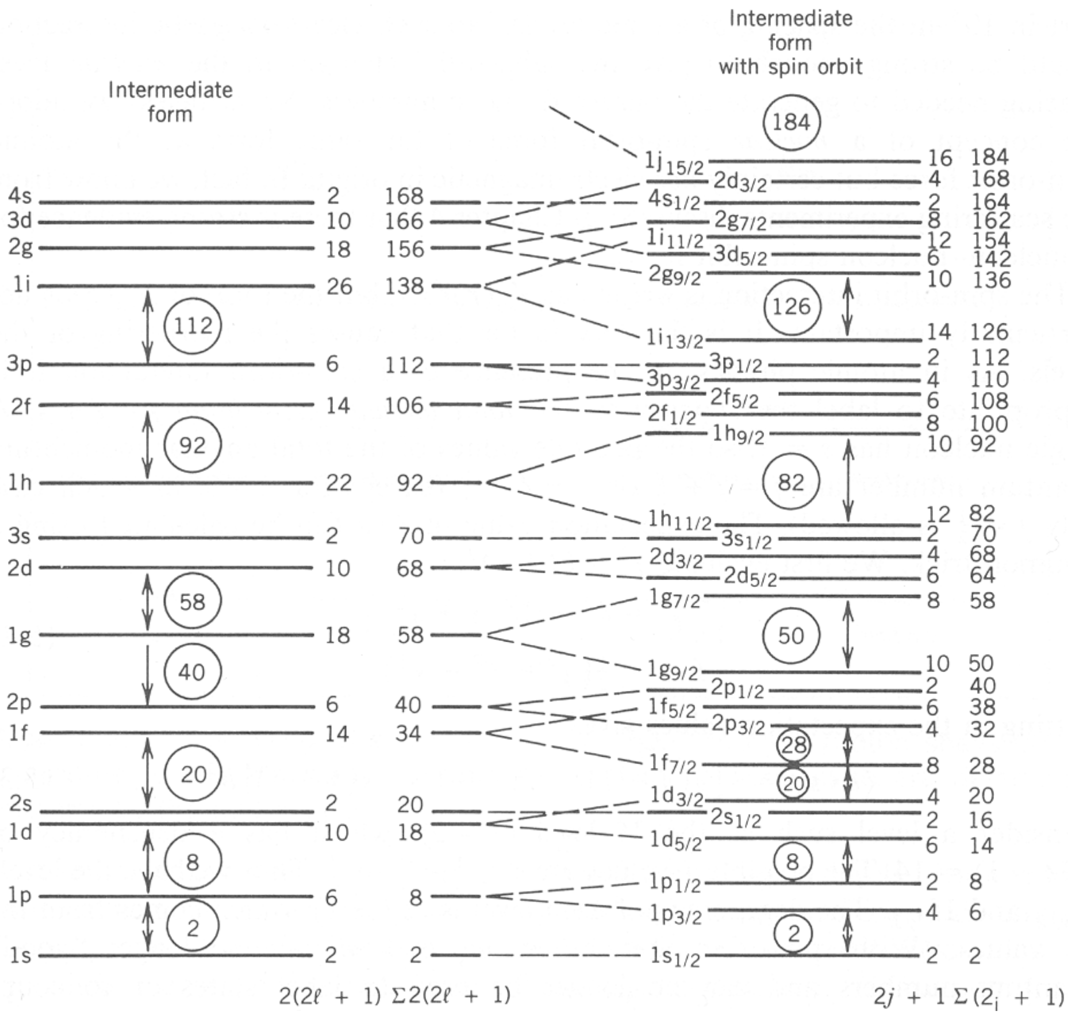
Spin-orbit coupling introduced

Could explain all the magic numbers

Maria Goppert-Mayer (1906-1972)

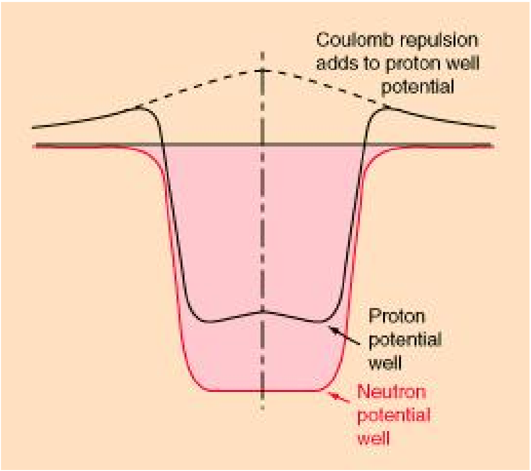
Spin-orbit coupling occurs when two motions are coupled together, such as the earth spinning on its axis as it orbits the sun. In an atom, the electron spins on an axis as it orbits the nucleus.

# Shell Model 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 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 in atoms. Gamma rays emitted.