PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 21900
General Physics II

Electricity, Magnetism and Optics
Lecture 27 – Chapter 28.1-3
Nuclear Structure

Fall 2015 Semester

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But First…

- de Broglie suggested that particles, like electrons, might have wave-like properties, just like light.

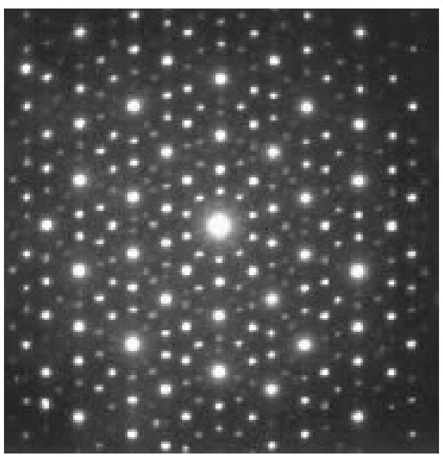
$$\lambda = \frac{h}{p}$$

- We never noticed this before, because λ is usually much smaller than any objects a particle will interact with.
- Davisson-Germer experiment:
  - Electron "waves" are scattered by planes of atoms in a crystal.
  - Constructive and destructive interference when electron waves are scattered by different planes
  - This works because the atomic spacing is similar to the de Broglie wavelength of the electron

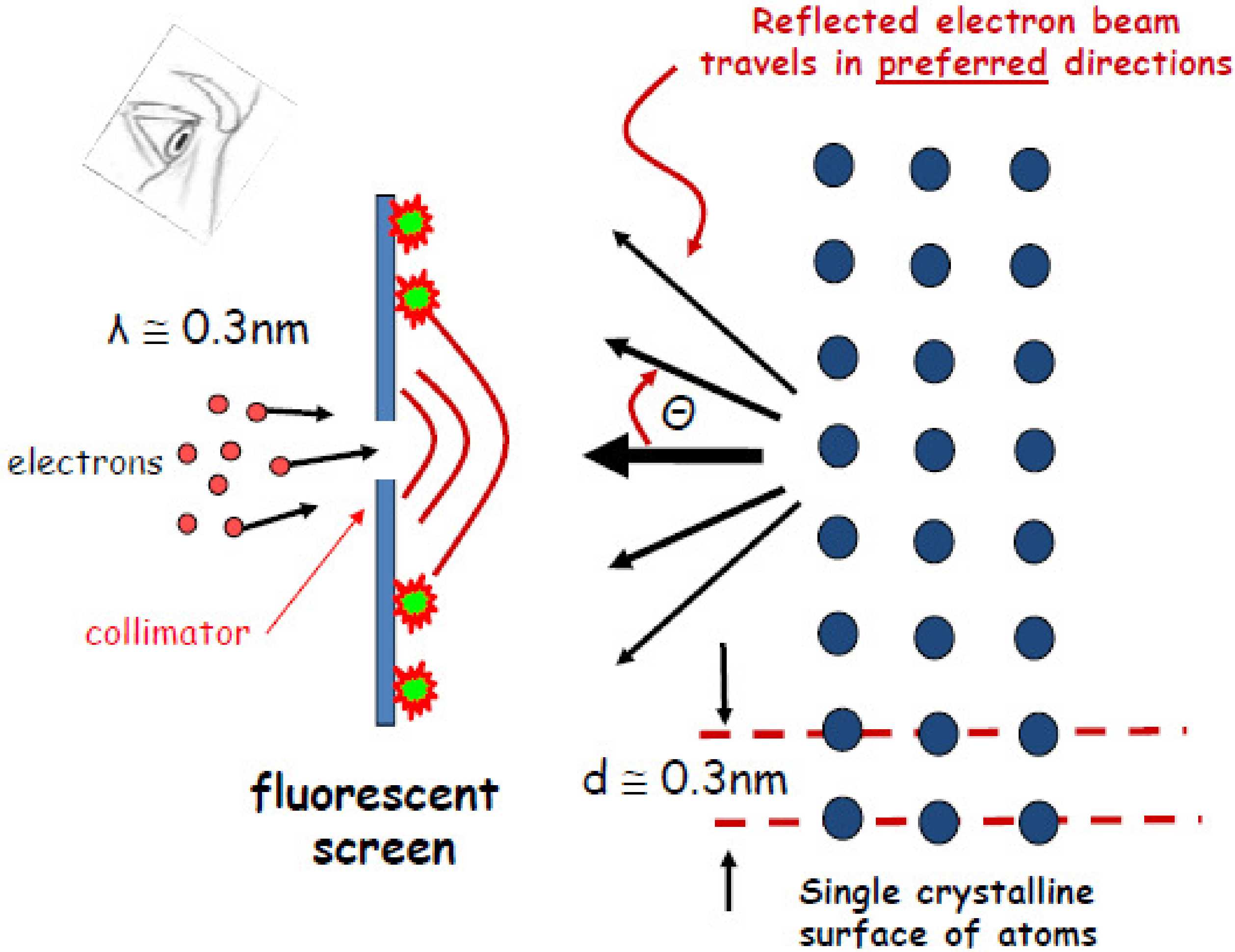
Davisson-Germer Experiment - 1927

Noble Prize 1937

Bell Telephone Laboratories



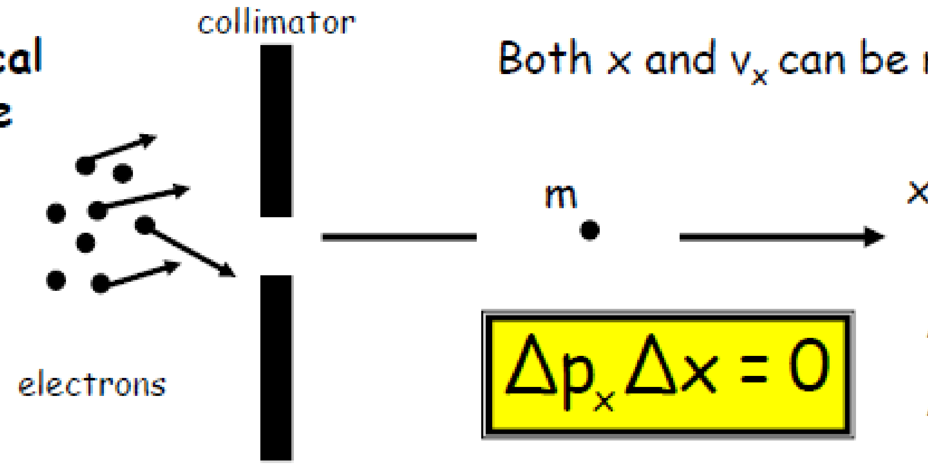
Representative photograph of screen



IF a particle behaves like a wave, it will be difficult to specify its position exactly

Heisenberg's Uncertainty Principle

Classical Picture



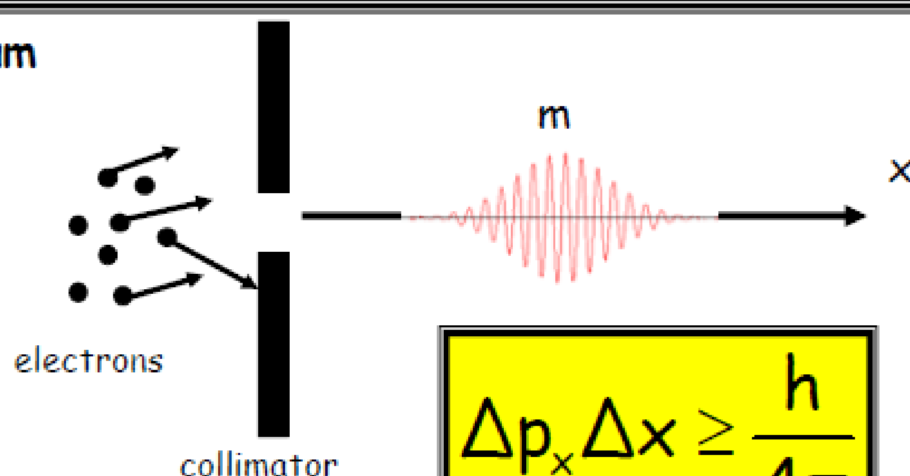
Both x and v_x can be measured exactly

$$\Delta p_x \Delta x = 0$$

Δp_x means uncertainty in p_x

Δx means uncertainty in x

Quantum Picture



$$\Delta p_x \Delta x \geq \frac{h}{4\pi}$$

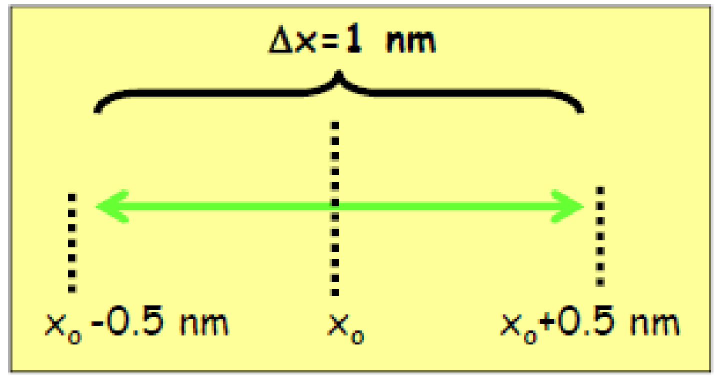
Specifies the **intrinsic** uncertainties in the **simultaneous** determination of position and momentum

EXAMPLE: A hydrogen gas molecule (H_2) at room temperature has an **average** velocity of about 1920 m/s. If the molecule (made from 2 H atoms) is localized to some position $\mathbf{x_o}$ within ±0.5 nm, what is the intrinsic uncertainty in its velocity?

$$m_{H_2} = 2m_p + 2m_e = 2(1.67\times10^{-27}\,\text{kg}) + 2(9.11\times10^{-31}\,\text{kg})$$

$$= 3.34\times10^{-27}\,\text{kg}$$

$$v_x = 1920\ {}^{m}\!/\!_{s} \quad \text{(given, but not needed)}$$



$$\Delta p_x \Delta x \ge \frac{h}{4\pi}$$

$$\Delta p_x \ge \frac{h}{4\pi}\frac{1}{\Delta x}$$

$$m_{H_2}\Delta v_x \ge \frac{h}{4\pi}\frac{1}{\Delta x} \Rightarrow \Delta v_x \ge \frac{h}{4\pi}\frac{1}{\Delta x}\frac{1}{m_{H_2}}$$

$$\Delta v_x \ge \frac{6.626\times10^{-34}\,\text{Js}}{4\pi}\cdot\frac{1}{1.0\times10^{-9}\,\text{m}}\cdot\frac{1}{3.34\times10^{-27}\,\text{kg}}$$

$$\Delta v_x \ge 16\ \text{m/s}$$

as $\Delta x \to 0, \quad \Delta v_x \to \infty$

Heisenberg Uncertainty Principle

The Heisenberg Uncertainty Principle is NOT a statement about the inaccuracy of measurement instruments, nor a reflection on the quality of experimental methods. Rather, it arises from the wave properties inherent in the quantum mechanical description of nature. Even with perfect instruments and technique, the uncertainty is inherent in the nature of things.

Nuclear Structure

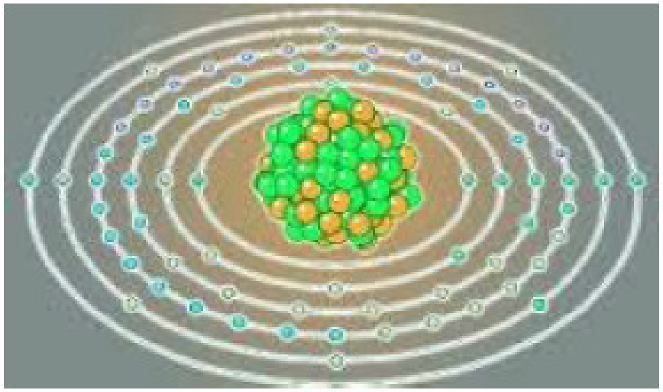
Number of chemical elements known in 1900: ~85

Number of chemical elements known today: ~118

About 91 are found naturally; 27 have been created in laboratories.

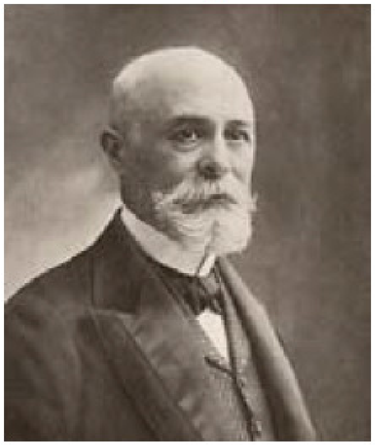
Most abundant on earth? Six elements account for 99% of the earth's mass: **oxygen, silicon, magnesium, iron, aluminum, and calcium**

How are the constituents of an atom arranged?



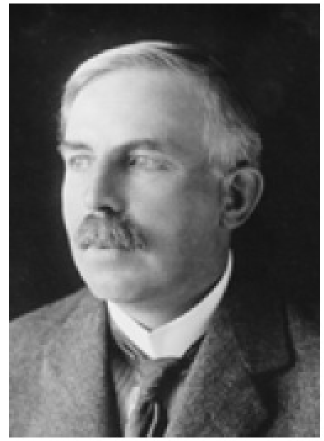
Early Studies of the Nucleus - Timeline

H. Becquerel



M. Curie

E. Rutherford



1895, Röntgen's discovery of X-rays

1896, Becquerel discovers that uranium salts emit **penetrating** X-ray-like radiation.

1898, Marie Curie isolates two radioactive chemical elements "polonium" and "radium" from a mineral called pitchblende (uranium oxide).

1899, Rutherford's experiments to study absorption of **penetrating** radiation.

Notable Dates

1901, Röntgen receives FIRST Noble Prize in Physics

1903, Marie Curie becomes the first woman to receive a doctorate degree in France.

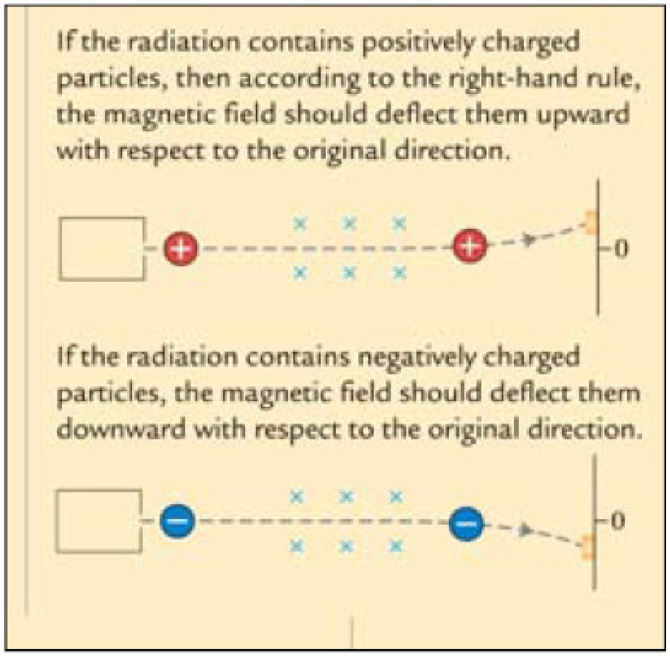
1903, Becquerel shares the Noble Prize in Physics with Marie Skłodowska-Curie and her husband Pierre Curie for the discovery of "spontaneous" radioactivity.

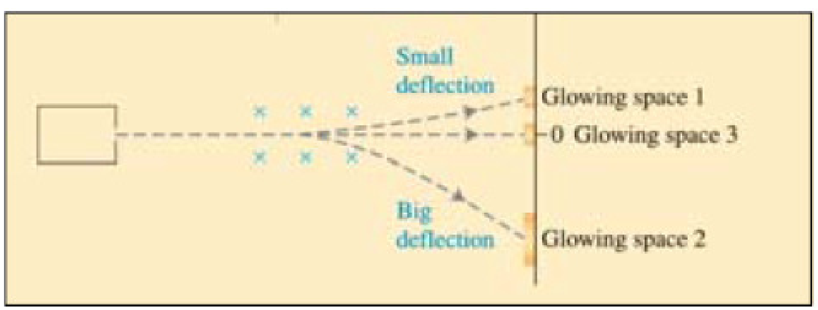
1908, Rutherford receives Nobel Prize in chemistry

1911, M. Curie receives 2nd Nobel Prize in Chemistry for her discovery of radium and polonium.

Emission of alpha particles, beta rays, and gamma rays from matter - Rutherford (1899)

Measuring the net charge on energetically emitted particles





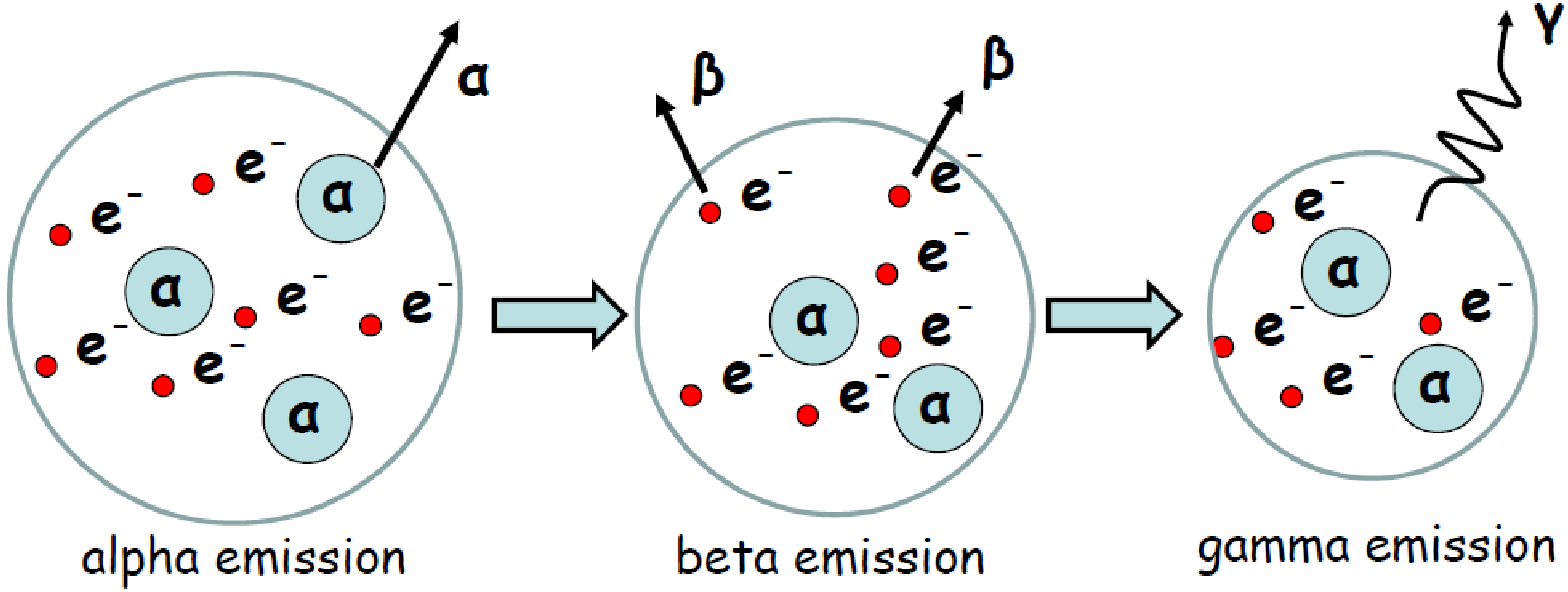
- Rutherford found the emission of energetic, positively charged particles that were named **alpha particles**. Alpha particles are equivalent to a He nucleus (2p, 2n).
- Emission of negatively charged particles were also observed. They had the same mass-to-charge ratio as an electron. They were called **beta rays**.
- Energetic emissions with NO charges were also detected. These "emissions" were thought to be high-energy electromagnetic waves, called **gamma rays**.

The earliest models of the atom

An atom was thought to consist of positively charged alpha particles and negatively charged electrons. The model was something like:

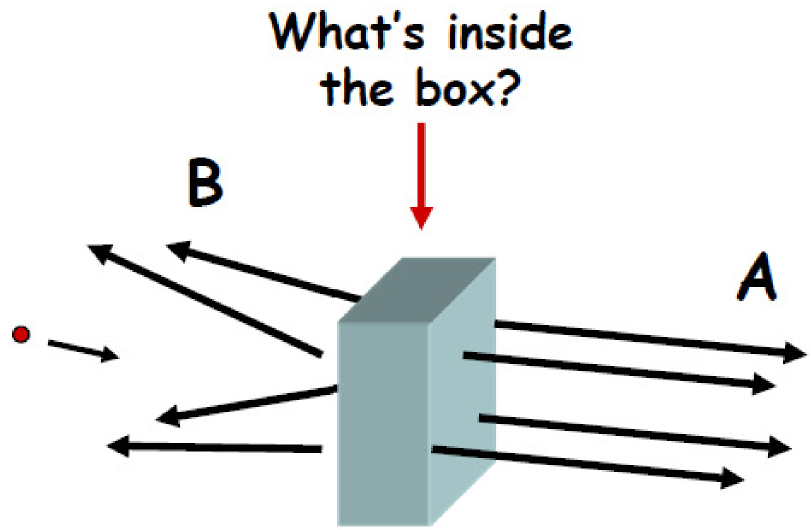
- When an atom contains a large number of alpha particles, they start repelling each other more strongly than the electrons can attract them, and an energetic **alpha particle** is ejected.
- Following **alpha emission**, the excess electrons repel each other; thus energetic electrons are emitted as **beta rays**.
- The atom is left in an excited state and relaxes to a lower energy state by emitting a high-energy photon, a **gamma ray**.

This model is incorrect!



Measuring the Size of the Nucleus

Scattering Experiments: The Basic Idea



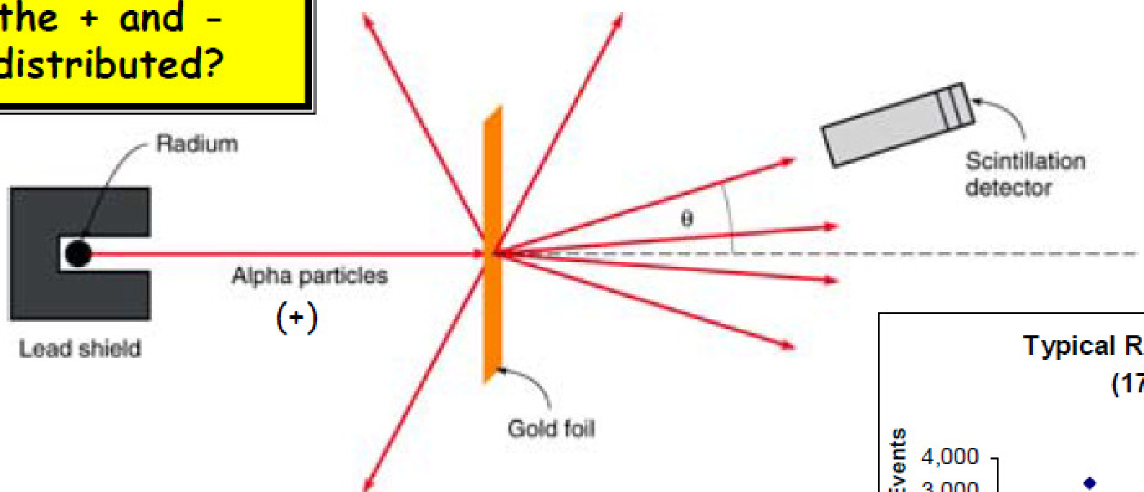
Two Limiting Scenarios:

- Result A: Box is filled with soft, fluffy material
- Result B: Box is filled with hard, rigid material

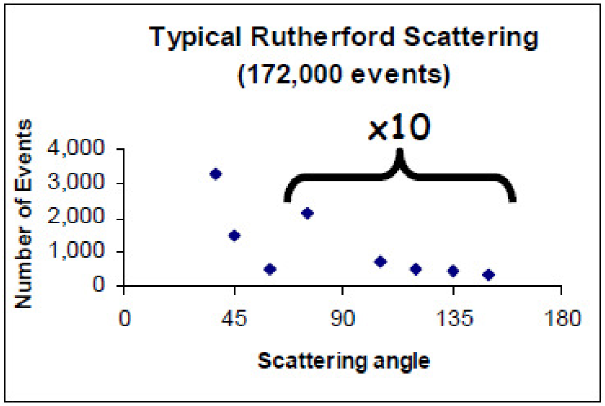
Evidence for a Massive Nucleus: Rutherford's Scattering Experiments

KEY QUESTION:
We know gold foil is made of gold atoms that are electrically neutral. But how are the + and - charges distributed?

(Rutherford 1911)



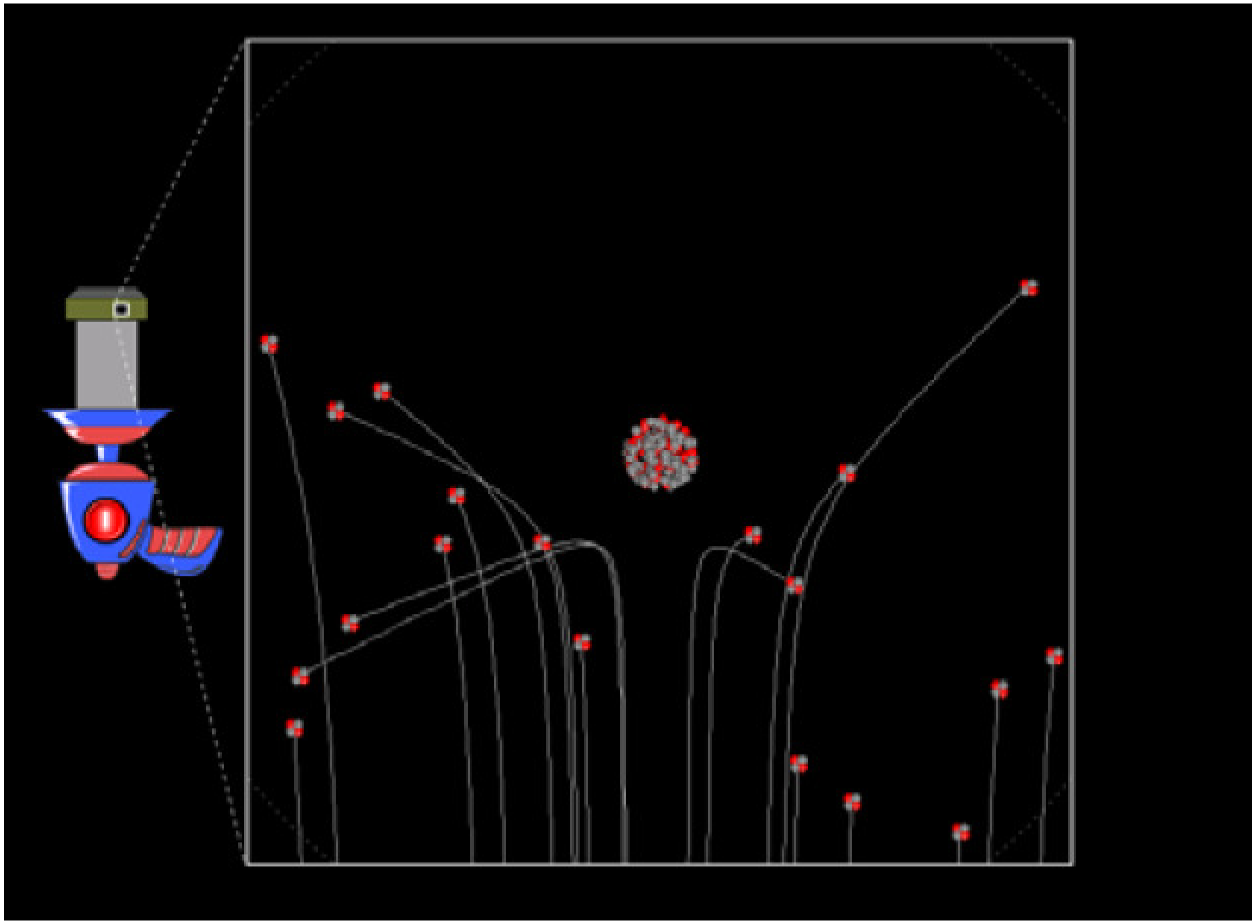
A few of the particles are backscattered!



Conservation of energy and momentum imply the presence of small "heavy objects". Rutherford concludes that the "heavy objects" are roughly ~10,000 times smaller than an atom!!

Rutherford Scattering Example

http://phet.colorado.edu/en/simulation/rutherford-scattering



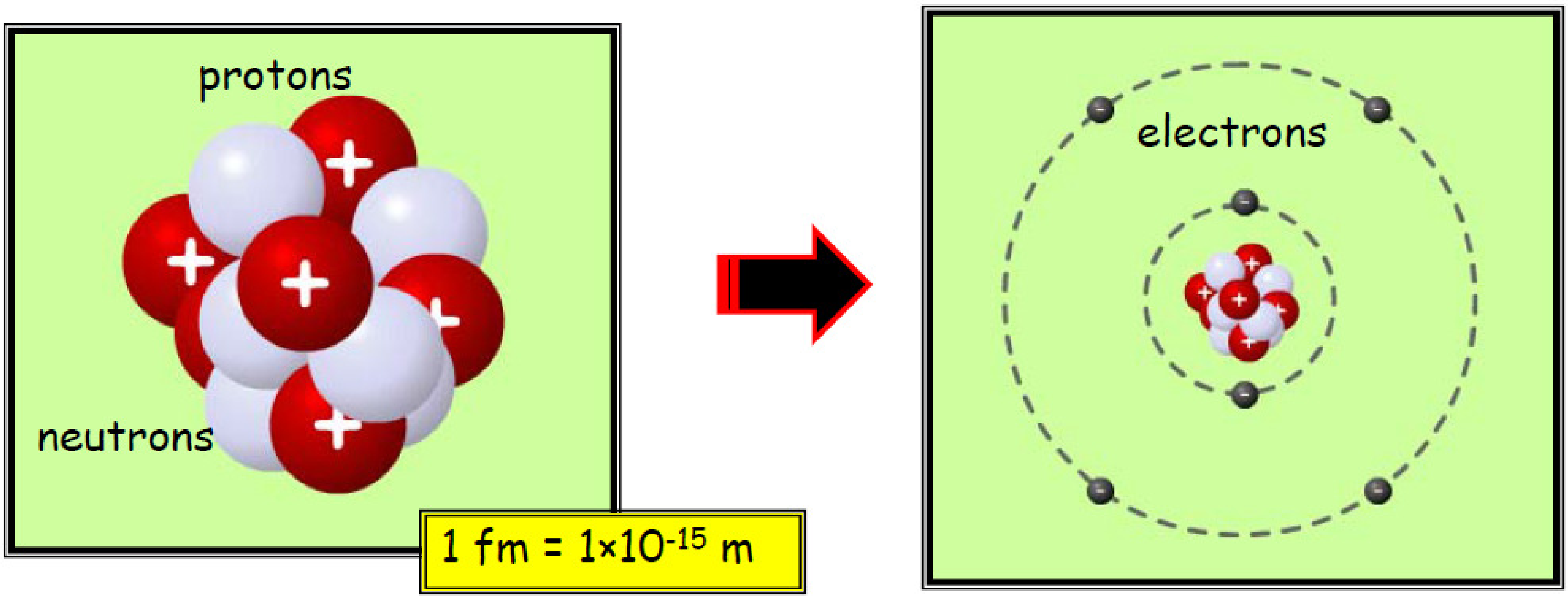
Conclusion: The nucleus must be very compact

Problem with the early model of the nucleus

One hydrogen atom is lighter than an alpha particle!! So the nucleus of H must NOT contain alpha particles. In 1911, Rutherford hypothesizes a proton. This suggestion plus Bohr's theory provides insight into the composition of an atom:

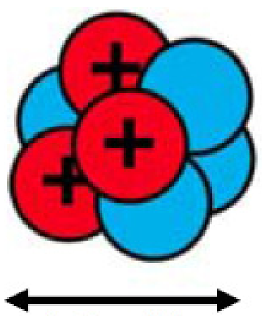
Rutherford's "heavy objects"
The "invention" of the nucleus
(diameter≅3 fm)

Bohr's orbits
Atom
(diamter≅0.2 nm)



Nucleons - the basic building blocks of the nucleus

Lithium-7 ($_3Li^7$)



~10^{-15} m

$$\begin{array}{rl} 3 & \text{protons} \\ \underline{4} & \text{neutrons} \\ 7 & \text{nucleons} \end{array}$$

Also written as: ^7_3Li

Examples:

X=Chemical Element

^A_ZX

$^{12}_6C$

$^{35}_{17}Cl$

A = mass number = Z+N

Z = number of protons = atomic number

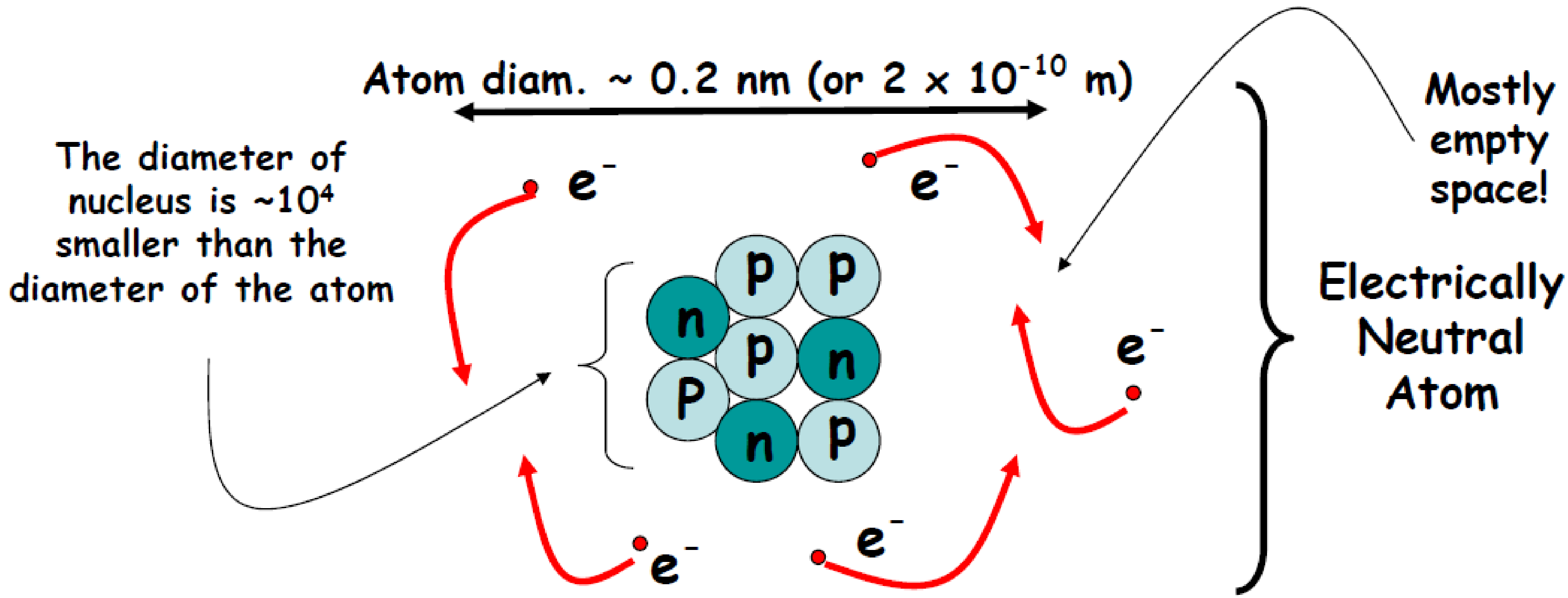
N= A-Z = number of neutrons

Isotopes - same element but different mass

	protons	neutrons	electrons	
$^{1}_{1}H$	1	0	1	Hydrogen
$^{2}_{1}H$	1	1	1	Deuterium (1 in 6000)
$^{3}_{1}H$	1	2	1	Tritium (1 in 10^{17})
$^{235}_{92}U$	92	143	92	U-235 (0.72%)
$^{238}_{92}U$	92	146	92	U-238 (99.27%)

More than 2000 isotopes have been identified!
About 400 are considered stable; about 1600 of them undergo radioactive decay.

Atoms of different elements have different masses: the internal structure of an atom



	neutron	proton	electron
symbol	n	p	e^-
charge	0 (zero)	$+1.602 \times 10^{-19}$ C	-1.602×10^{-19} C
mass	1.675×10^{-27} kg	1.673×10^{-27} kg	9.109×10^{-31} kg

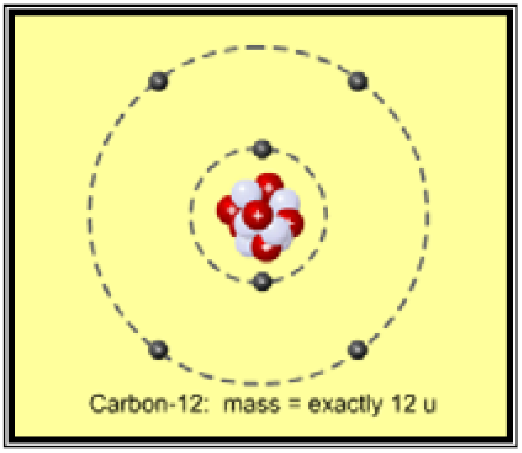
Notes: 1 C = 1 Coulomb; $m_p + m_e = 1.674 \times 10^{-27}$ kg

Diagram not to scale

Nuclear masses are very tiny ($\sim 10^{-28}$ kg); invent a new unit of mass - the atomic mass unit (amu) or unified mass unit (u)

Consider Carbon-12:

$$^{12}_{6}C$$



Define new mass unit as

1 u = 1.660540×10^{-27} kg

With this definition, the mass of $^{12}_{6}C$ is exactly 12.000u

m_p=1.007276 u; m_n=1.008665u; m_e=0.00055u

What are the approximate masses of the following nuclei?

These symbols do not represent atoms, they represent nuclei.

$^{A}_{Z}X$

$^{4}_{2}He$

Helium: 2 protons, 2 neutron, 4 nucleons:
$M \approx 4u = 4\ (1.66\times10^{-27}\ kg) = 6.64\times10^{-27}\ kg$

$^{35}_{17}Cl$

Chlorine: 17 protons, 18 neutron, 35 nucleons:
$M \approx 35u = 35\ (1.66\times10^{-27}\ kg) = 5.81\times10^{-26}\ kg$

$^{139}_{56}Ba$

Barium: 56 protons, 83 neutron, 139 nucleons:
$M \approx 139u = 139\ (1.66\times10^{-27}\ kg) = 2.31\times10^{-25}\ kg$

A new concept – rest mass energy

Einstein showed that mass and energy are equivalent according to his famous equation

$$E=mc^2$$

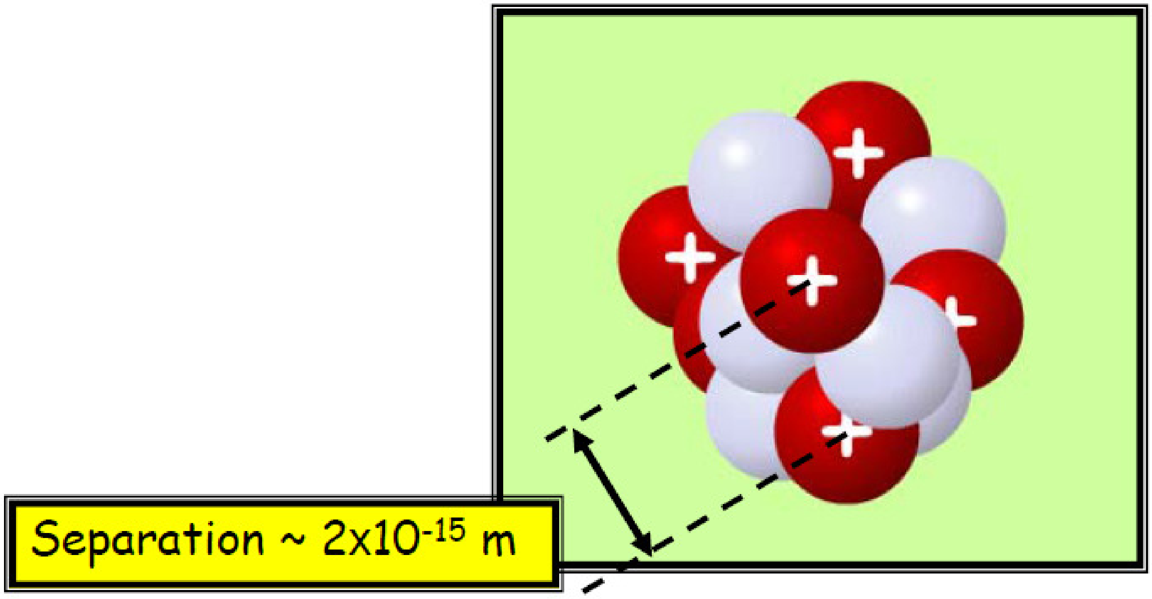
It follows that the tiny nuclear masses are equivalent to huge amounts of energy.

Example: Calculate the rest mass energy of a proton.

$$E_{\text{rest mass}} = m_p c^2 = 1.007276\,\text{u}\left(\frac{1.660539\times10^{-27}\,\text{kg}}{1\text{u}}\right)\left(2.998\times10^{8}\,\text{m}\,\text{s}^{-1}\right)^2 = 1.503\times10^{-10}\,\text{J}$$

$$= 0.15\text{nJ}\left(\frac{1\,\text{eV}}{1.602\times10^{-19}\,\text{J}}\right) = 9.383\times10^{8}\,\text{eV} = 938.3\,\text{MeV}$$

Coulomb Repulsive Force between Protons is Huge

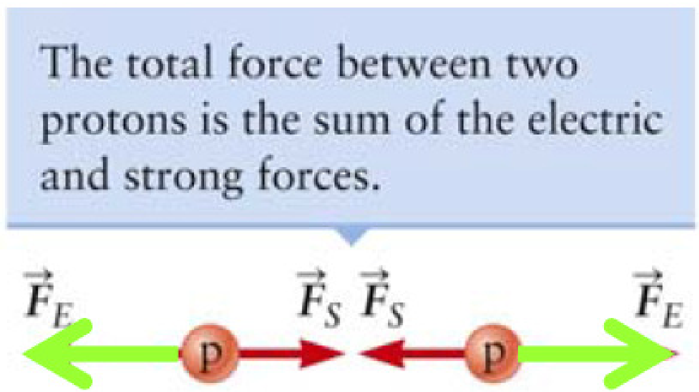


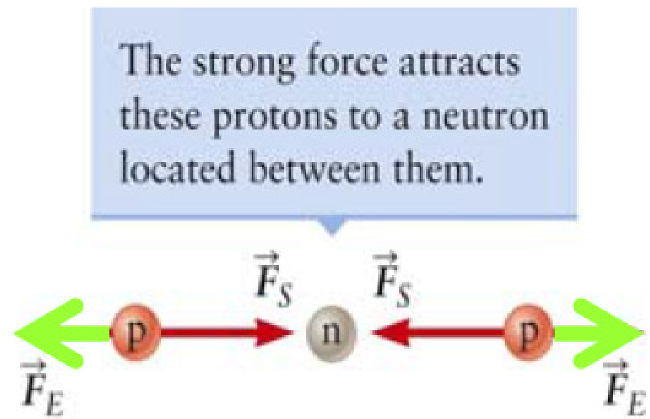
$$F_{electrostatic} = k\frac{q_1 q_2}{r^2} = 9\times10^9 \frac{\left(1.6\times10^{-19}\right)^2}{\left(2\times10^{-15}\right)^2}$$

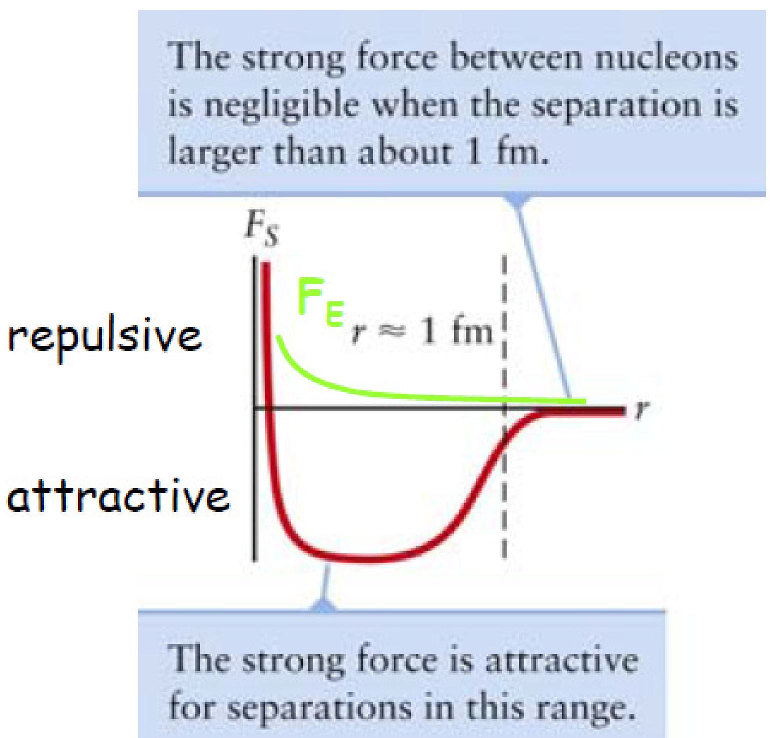
$$= 58N \bullet \frac{0.22\ lbs}{1\ N} \simeq 12.6 \text{ lbs of force}$$

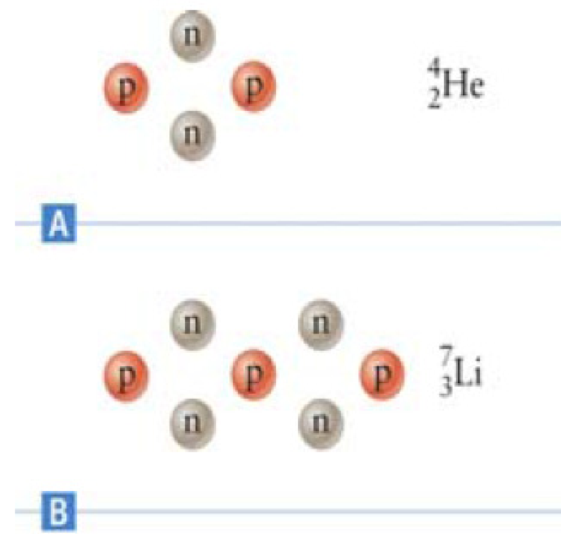
The strong force acts between nucleons

(Chadwick 1932, Yukawa 1935)









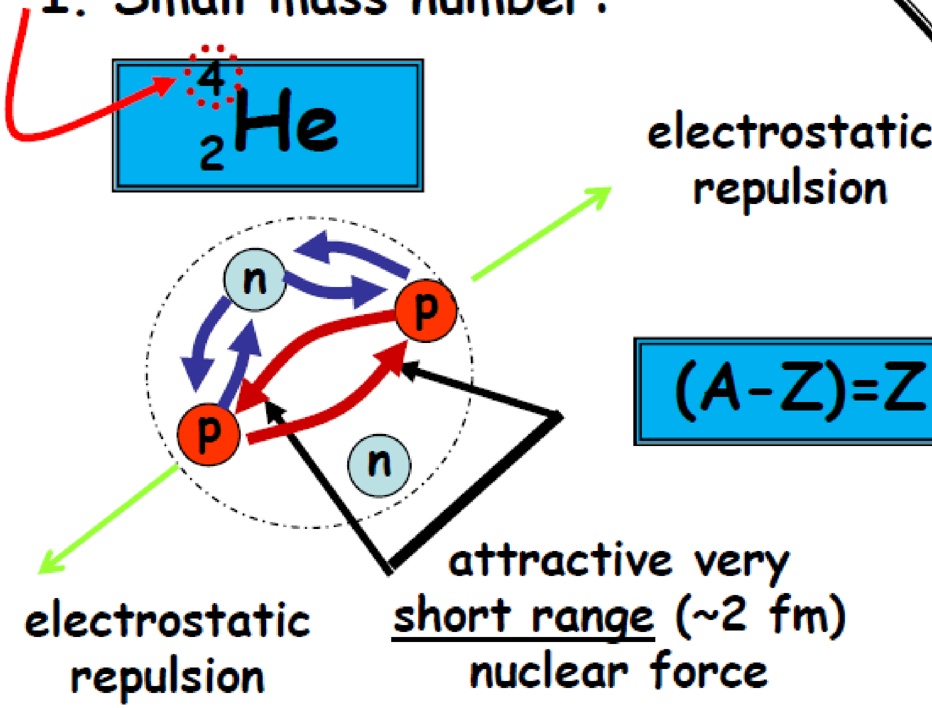
Neutrons i) increase distance between protons and ii) act as a glue to hold nucleus together.

Nuclear Binding - The strong force

n neutron

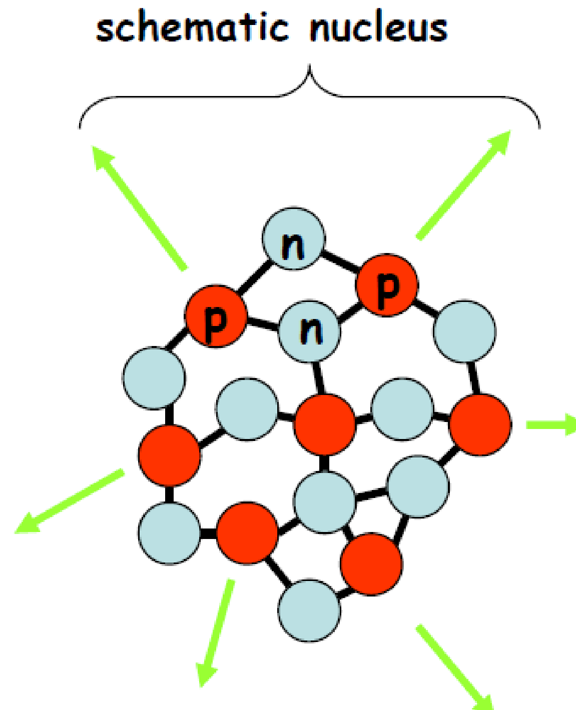
p proton

I. Small mass number:



(A-Z)=Z

II. Large mass number:



As size of nucleus increases, more neutrons are required to hold it together

(A-Z)>Z

Nuclear size; Nuclear density

Many experiments indicate the nucleus is roughly **spherical** with a radius given by

$$r = r_o A^{1/3}; \quad r_o = 1.2 \times 10^{-15}\ m$$

What is the nuclear mass density of the most common isotope of iron?

$$^{56}_{26}Fe \Rightarrow A = 56$$

$$\rho_{Fe\ nucleus} = \frac{m_{nuc}}{V_{nuc}} \simeq \frac{A \cdot u}{\frac{4}{3}\pi r^3} = \frac{3A \cdot u}{4\pi (r_o A^{1/3})^3} = \frac{3\cancel{A} \cdot u}{4\pi r_o^3 \cancel{A}} = \frac{3u}{4\pi r_o^3}$$

$$= \frac{3 \times 1.66 \times 10^{-27}\, kg}{4 \times 3.14 \times (1.2 \times 10^{-15}\, m)^3} \simeq 2.3 \times 10^{17}\, kg/m^3$$

Nuclear density is constant, independent of A!

Typical Densities

Material	Density
Helium	0.18 kg/m^3
Air (dry)	1.2 kg/m^3
Styrofoam	~100 kg/m^3
Water	1000 kg/m^3
Iron	7870 kg/m^3
Lead	11,340 kg/m^3
Nuclear Matter	***~10^{17} kg/m^3***