Spring, 2016

Osher Five Lecture Series

Russell Doolittle

Lecture 1: Avogadro's Number

Lecture 2: The Discovery of X-Rays

Lecture 3: Nature of the Atomic Nucleus

Lecture 4: Sickle Cell Anemia: a Molecular Disease

Lecture 5: Unraveling the Genetic Code

Osher Lecture 3

Nature of the Atomic Nucleus

Russell Doolittle

May 4, 2016

In the last decades of the 19th century, the nature of rays and particles, space and waves, atoms and molecules, remained very much a puzzle.

1895	Discovery of X-rays	Roentgen	Germany
1896	Discovery of radioactivity	Becquerel	France
1897	Characterization of electron	Thompson	England

In all these inquiries, the electrical and magnetic properties of "rays" (radiation) and the nature of "waves" were fundamental.

In 1910 Rutherford (working in England) made a discovery that would lead to a remarkable model that eventually showed what distinguishes one element's atoms from others.

In 1874, G. Johnstone Stoney, read a paper before the Royal Society (England) in which he gave a new interpretation of Faraday's well known electrolysis experiments.

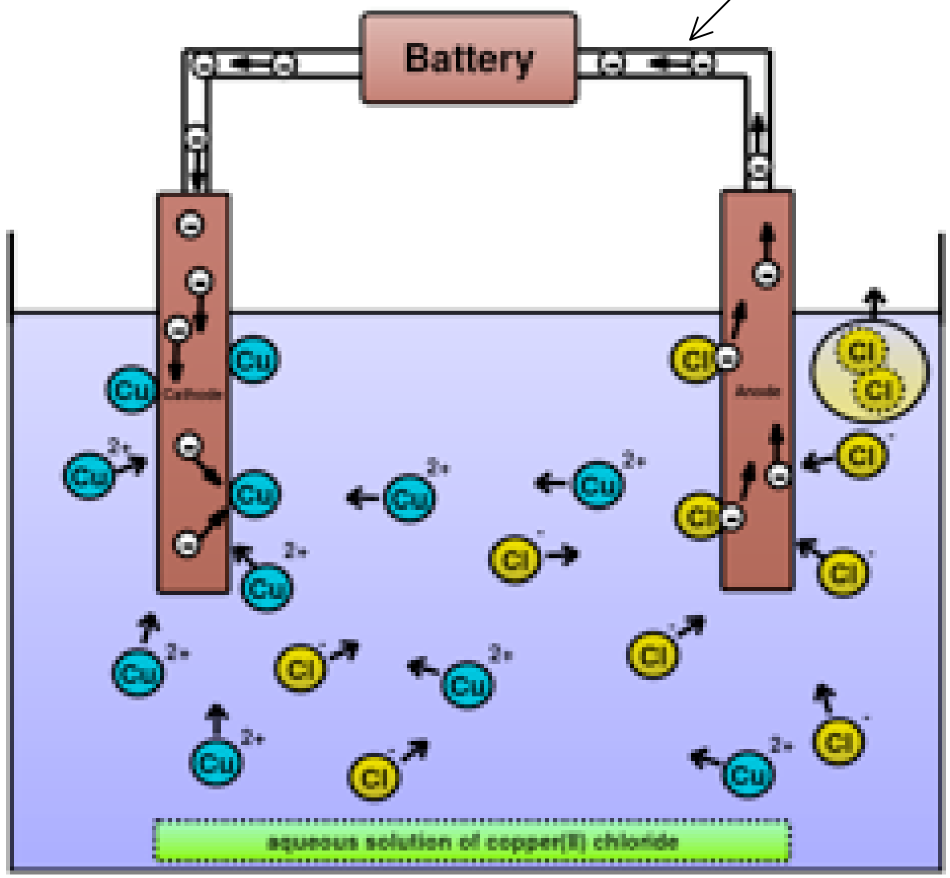
The novelty was that the amount of electric current needed to deposit a specified amount of some chemical ought to translate into whole number amounts of charge, i.e., a substance might have 0, 1, 2, etc. charges per molecule.

In fact, he said, the electric current itself must be made of particles, and in 1891 he named the particle the *electron*.

1833: Michael Faraday

Electrolysis

Stoney declares electricity made of particles called electrons



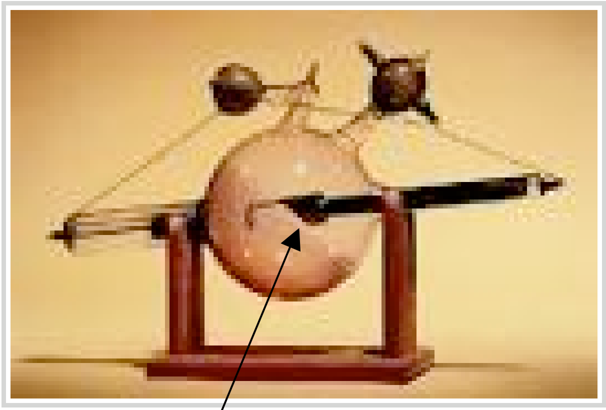
In 1896, upon learning of Roentgen's report of a new kind of radiation (X-rays), J. J. Thompson immediately had a similar apparatus constructed.

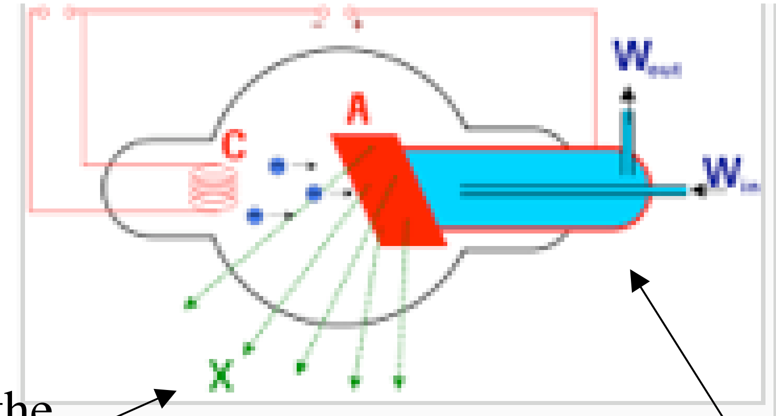
The first thing he did was to pass the X-rays through a second electrified vacuum tube with a gas in it (fitted with a low voltage battery).

Before exposure to X-rays, the various gases he tried were *non*-conducting.

After exposure to X-rays, the various gases he tried were *conducting*, which is say they were *ionized*.

Thompson's first X-ray tube





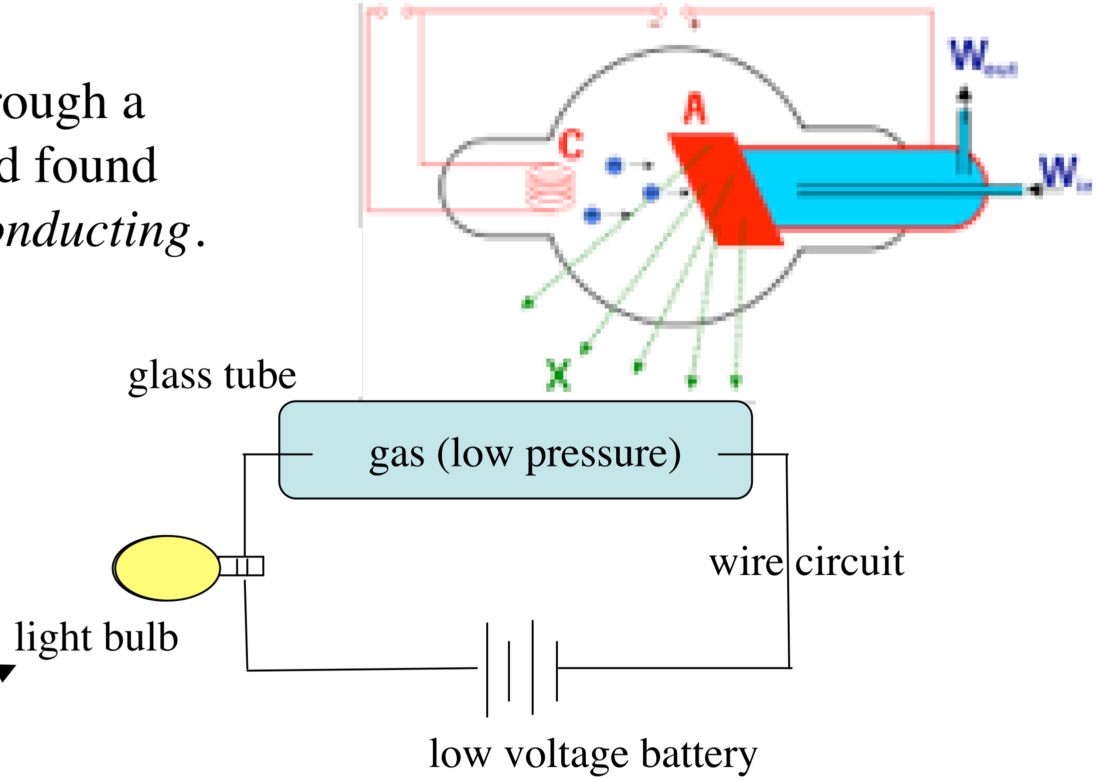
The anode was fashioned such that the X-rays came out here and could be aimed.

A water jacket was built in to cool the anode.

He applied a very high voltage in order to generate the X-rays, and as a result the anode would heat up from the intense collisions.

Thompson’s first experiment with X-rays

He directed X-rays through a gas at low pressure and found that the gas became *conducting*.

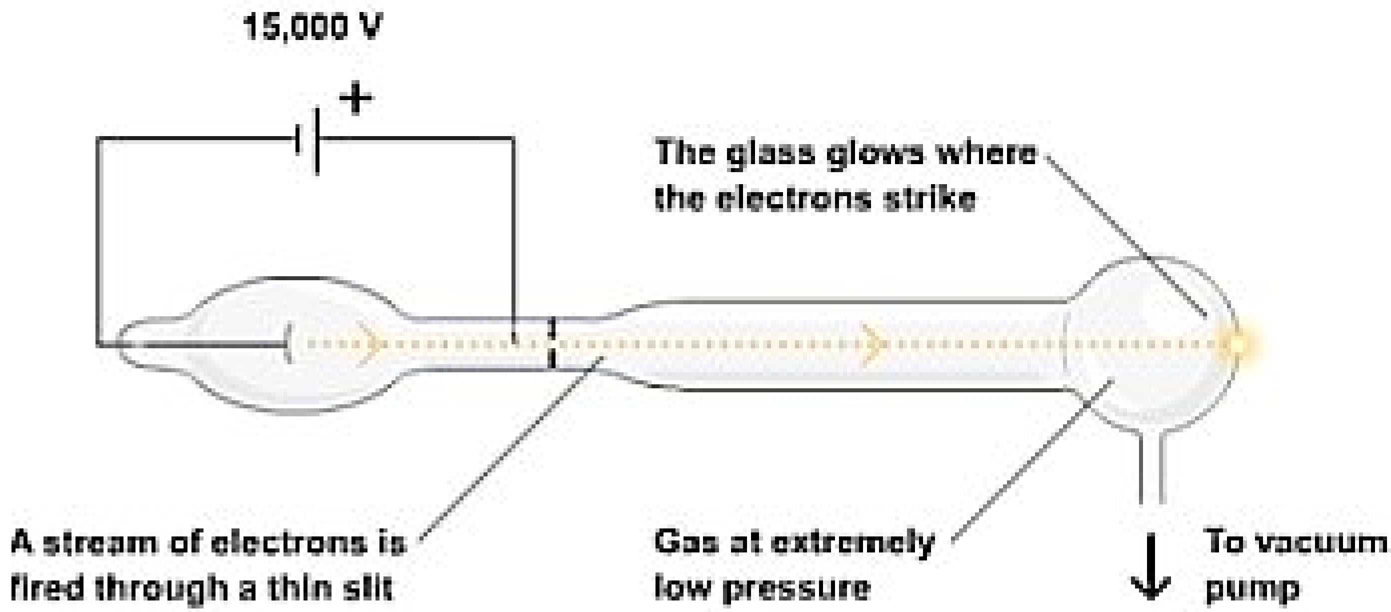


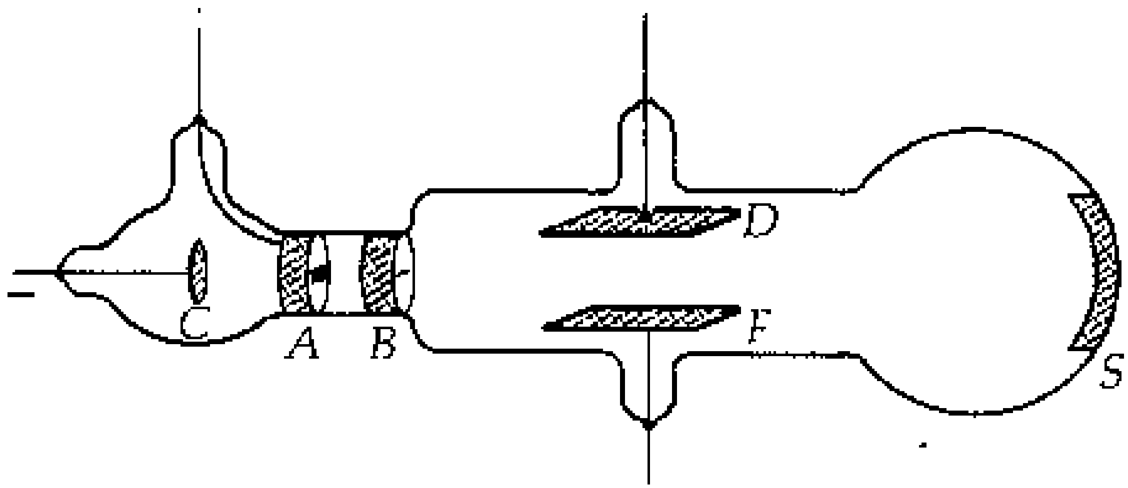
The light bulb would glow after being X-rayed.

In today’s vocabulary, the gas had become *ionized*.

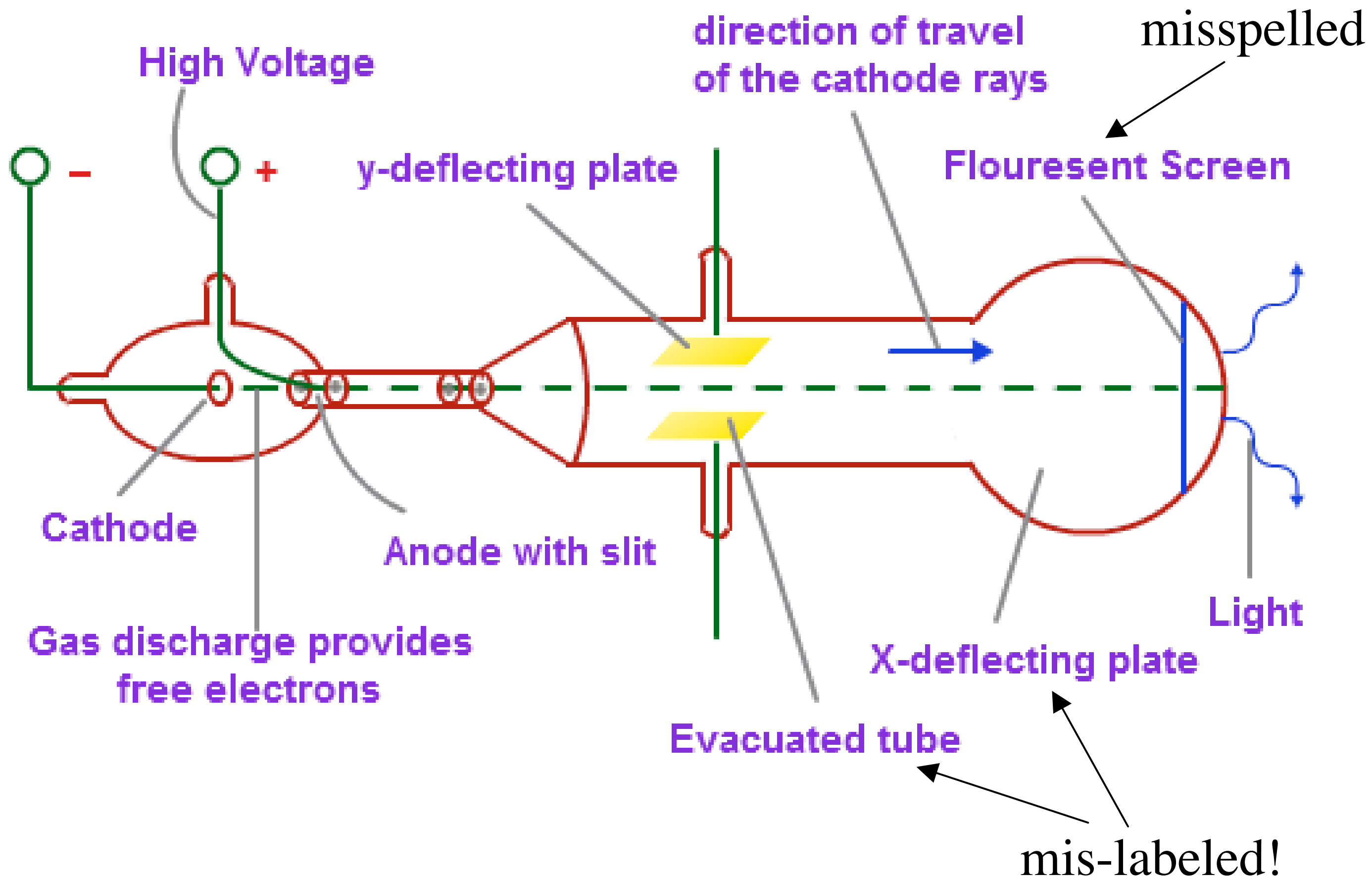
At that point Thompson backed up to try and figure out what the cathode rays were, which he figured must be the electric particles Stoney had named electrons.

1897 JJ Thompson proves electrons are atoms of electricity.





Thomson's tube for measuring q/m for the particles of cathode rays (electrons). Electrons from the cathode C pass through the slits at A and B and strike a phosphorescent screen S. The beam can be deflected by an electric field between plates D and F or by a magnetic field (not shown).


High Voltage
–
+
direction of travel
of the cathode rays
misspelled!
y-deflecting plate
Flouresent Screen
Cathode
Anode with slit
Gas discharge provides
free electrons
Light
X-deflecting plate
Evacuated tube
mis-labeled!

Discovery of the Electron (1897)

J.J. Thompson was able to determine that cathode rays were negatively charged particles with masses that were about 1/1000th that of hydrogen molecules. How did he do this?

First he bent the beam away from the center with a positively charged plate. Then he brought it back into the center by balancing the electrical deflection with an appropriately situated magnet.

Then he did some algebra for the two kinds of force on a particle moving in a vacuum, the result of which was the charge/mass ratio (Q/m) .

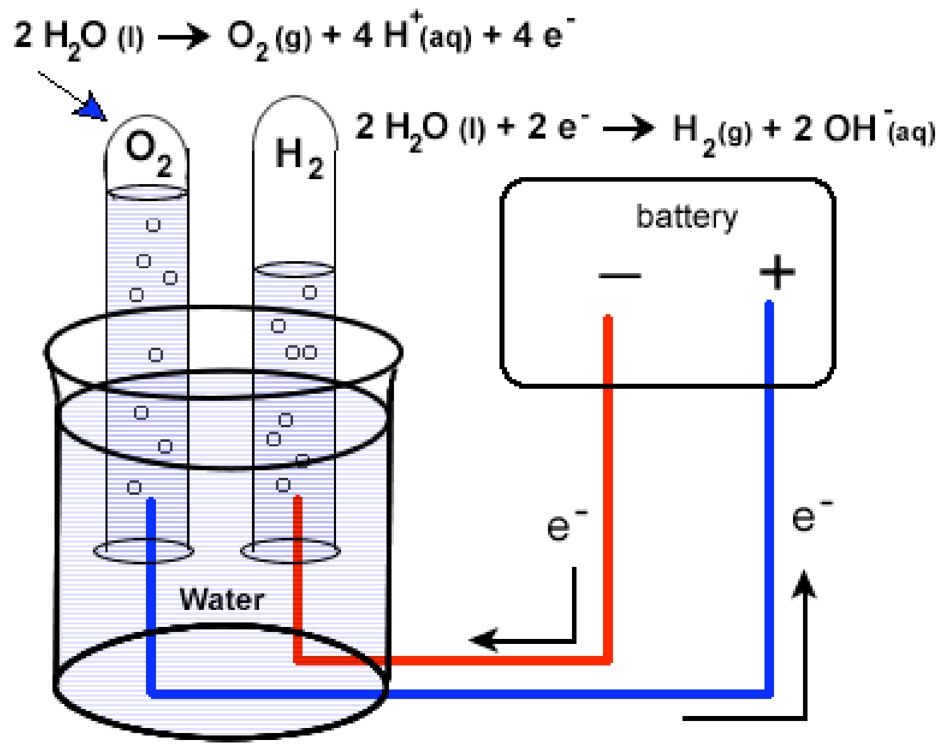
$$F = Q(E + vB) \qquad F = ma$$

Q = electric charge, E is the strength of electric field, v = velocity of particle and B is strength of magnetic field.

The charge/mass ratio for hydrogen was already known, based on how much electricity it took to electrolyze a known amount of water.

Electrolysis

A known amount of electricity gave rise to a known amount of hydrogen (and oxygen).



To get started, the charge/mass ratio for hydrogen was given a value of 1.0 coulomb/gram

The charge/mass ratio for Thompson's cathode ray particle (electron) was 10^8 coulomb/gram

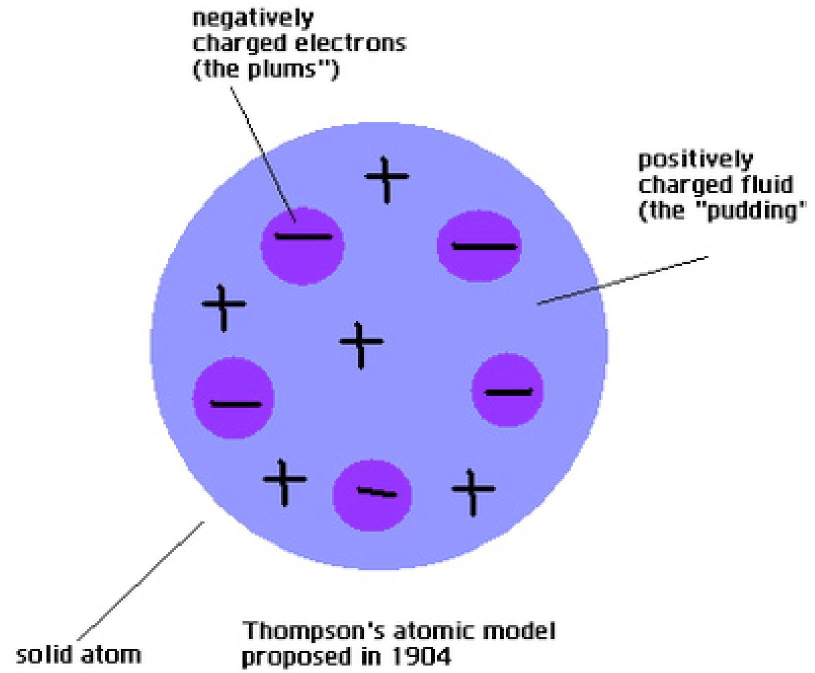
It requires 96,500 coulombs to obtain a gram of hydrogen gas by electrolysis (Faraday).

Accordingly, 10^8 / 9.7×10^4 is about 1,000 times more charge per mass, or 1,000 times lighter!

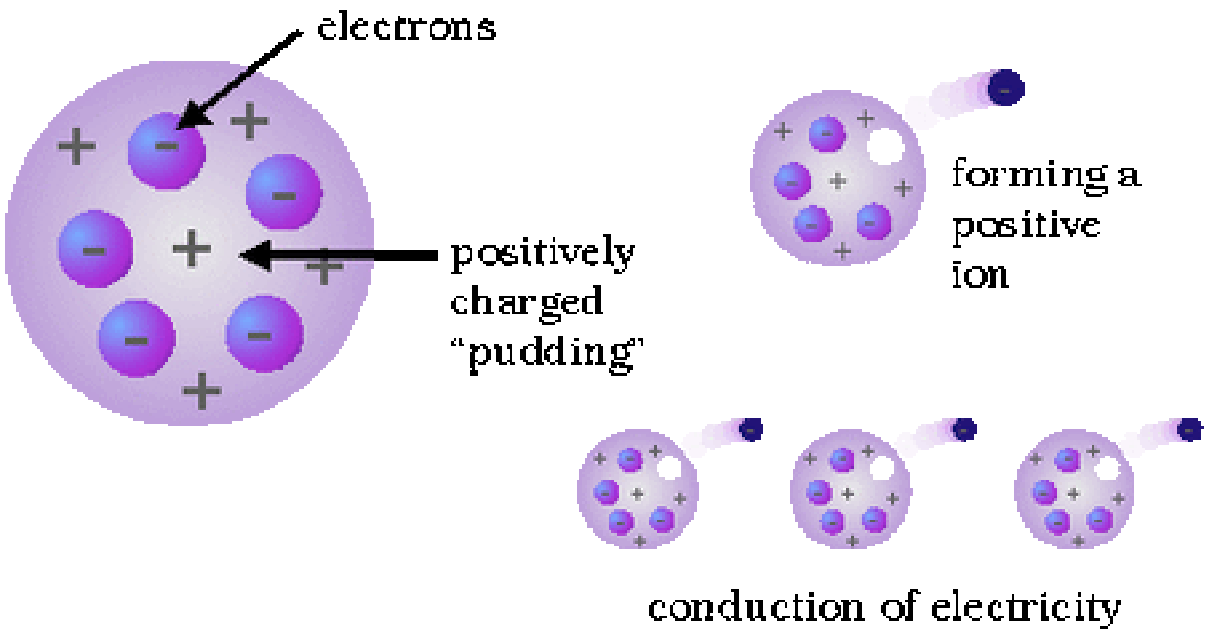
Of course, the hydrogen generated by the hydrolysis of water was diatomic. So the mass/charge ratio of the electron was really about 1/2000ths that of an ionized hydrogen (atom).

Thompson realized that there had to be one electron for every positive charge in a neutral atom. The presumption was they were equitably disposed in space: the “plum pudding” model.

Thompson proposed that atoms were positively charged spheres in which were embedded negatively charged electrons.



Thomson's Plum Pudding Atom

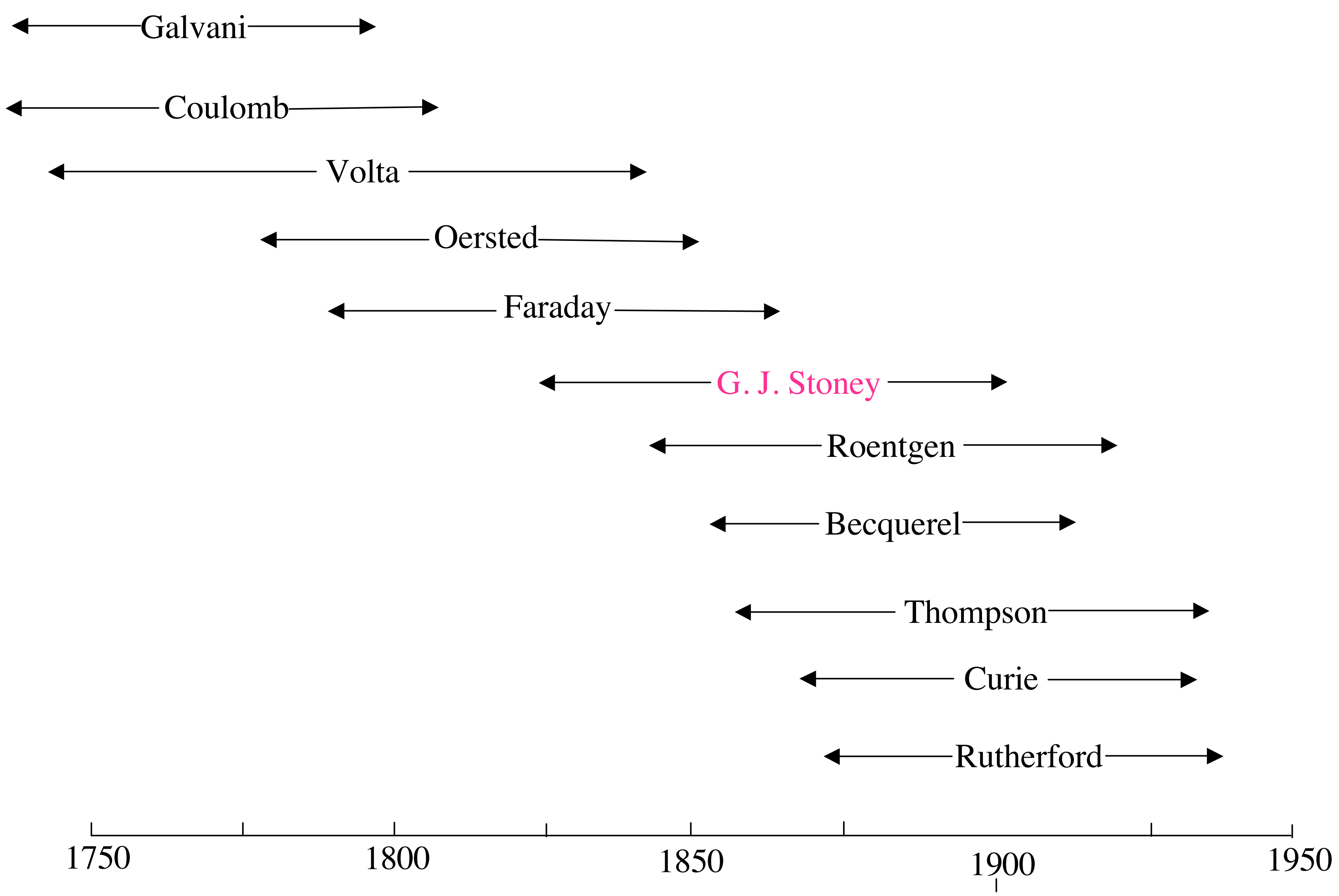


This model was in accord with his experiments showing that X-rays rendered gases *conducting*.

Stoney had actually made the following calculation earlier when Avogadro's number (N) had become known:

$$e = \text{Faraday}/N = 9.6 \times 10^{4} / 6 \times 10^{23} = 1.6 \times 10^{-19} \text{ coulombs}$$

In 1911 Millikan (oil drop experiment) determined the absolute charge on the electron to be 4.8×10^{10} esu $= 1.6 \times 10^{-19}$ coulombs!


Galvani
Coulomb
Volta
Oersted
Faraday
G. J. Stoney
Roentgen
Becquerel
Thompson
Curie
Rutherford
1750
1800
1850
1900
1950

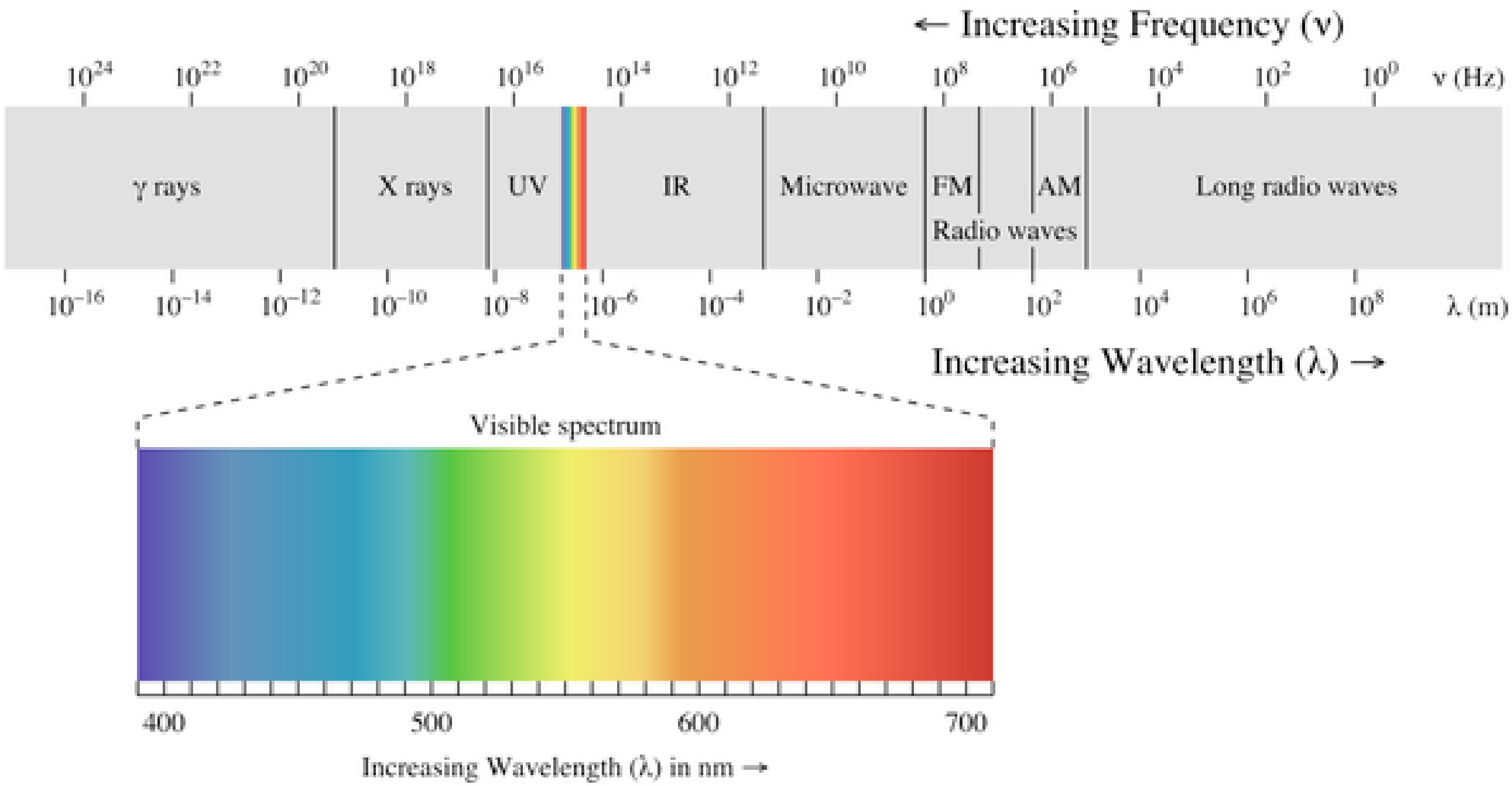
Discovery of Radioactivity (1896)

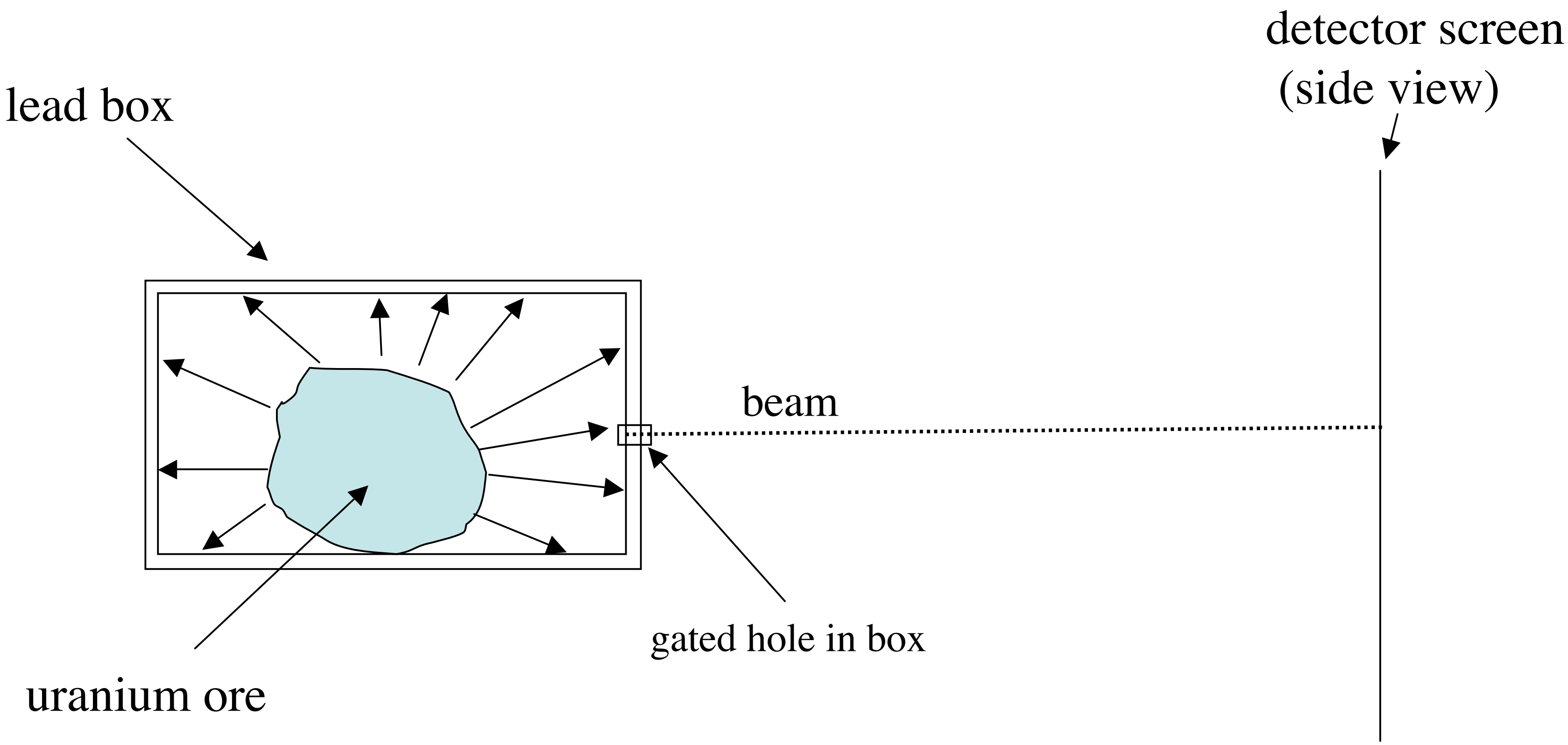
Henri Becquerel studying fluorescent minerals (rocks that glowed when light shone on them) .

He tested to see if any of them gave off “penetrating rays”.

None did, except for one that happened to contain uranium.

But it had nothing to do with the “glow” (fluorescence).

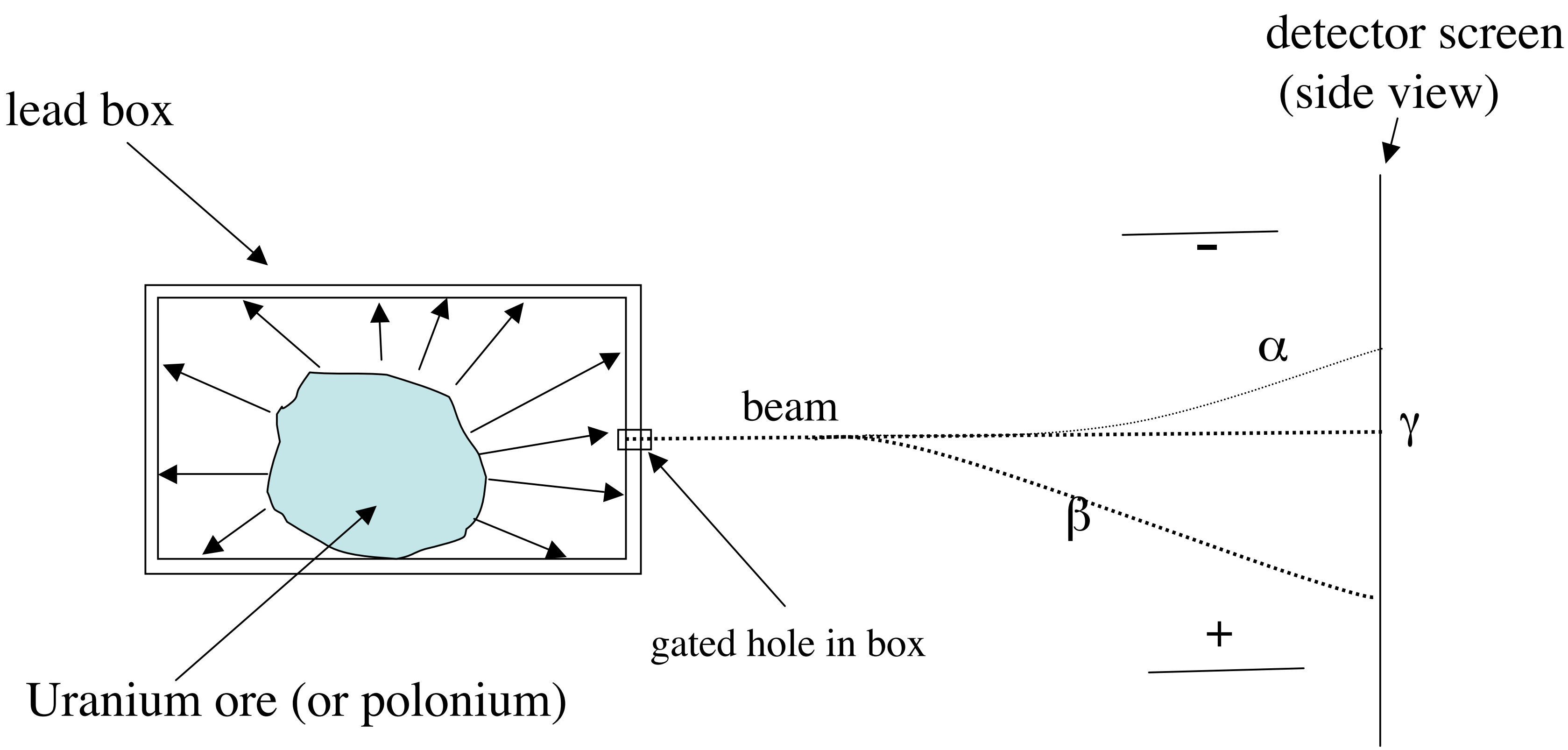

← Increasing Frequency (ν)
10^24 10^22 10^20 10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^−16 10^−14 10^−12 10^−10 10^−8 10^−6 10^−4 10^−2 10^0 10^2 10^4 10^6 10^8 λ (m)
Increasing Wavelength (λ) →
Visible spectrum
400
500
600
700
Increasing Wavelength (λ) in nm →



It was found that three kinds of radiation were emerging from the hole.

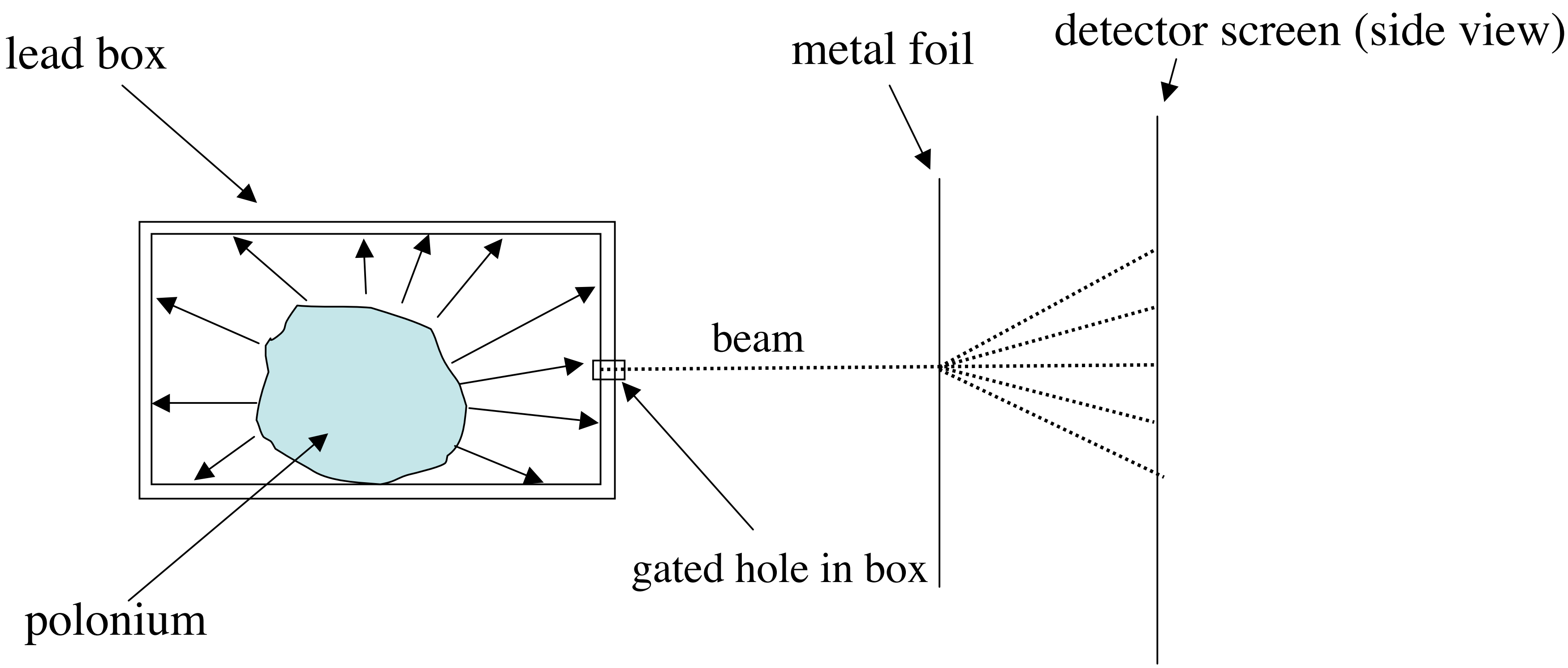
Some of the emergent rays were unaffected by electric or magnetic fields and called γ rays.

Some of the emergent rays were negatively charged and had the same charge/mass ratio as an electron. These were called β.



But some of the emergent rays were positively charged and had the same charge/mass ratio as the nucleus of a helium atom. These were called α.

[Avogadro's number could be calculated by measuring the volume of helium that corresponded to a counted number of α particles.]



Rutherford bombarded various metal foils with α particles to test their penetrating ability. Some of the particles were “scattered.”

Ernest Rutherford was not looking for the atomic nucleus.

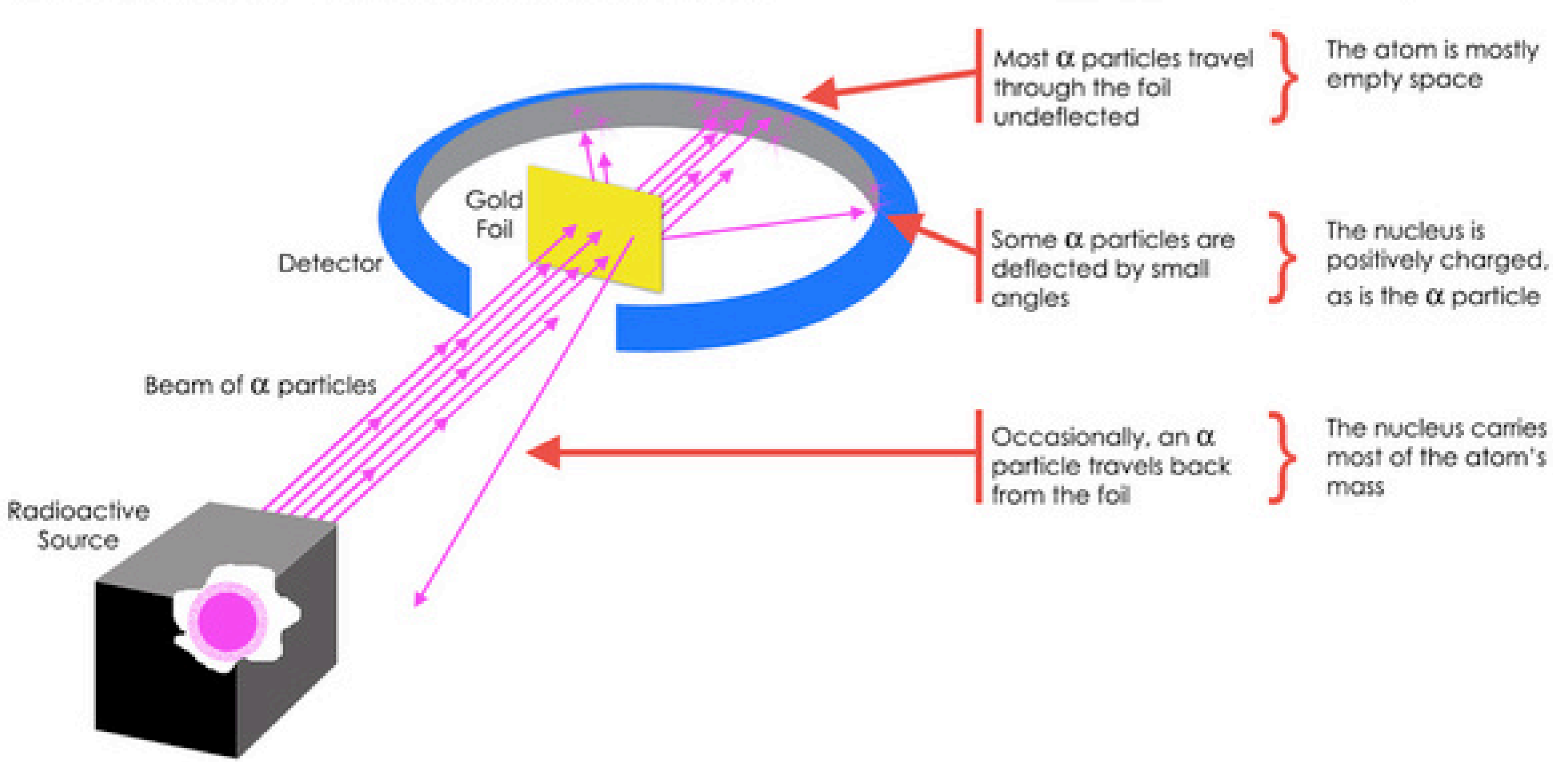
The experiment that led to its discovery could very well not have been performed.

Rutherford's Description of 1910 Events in His Laboratory

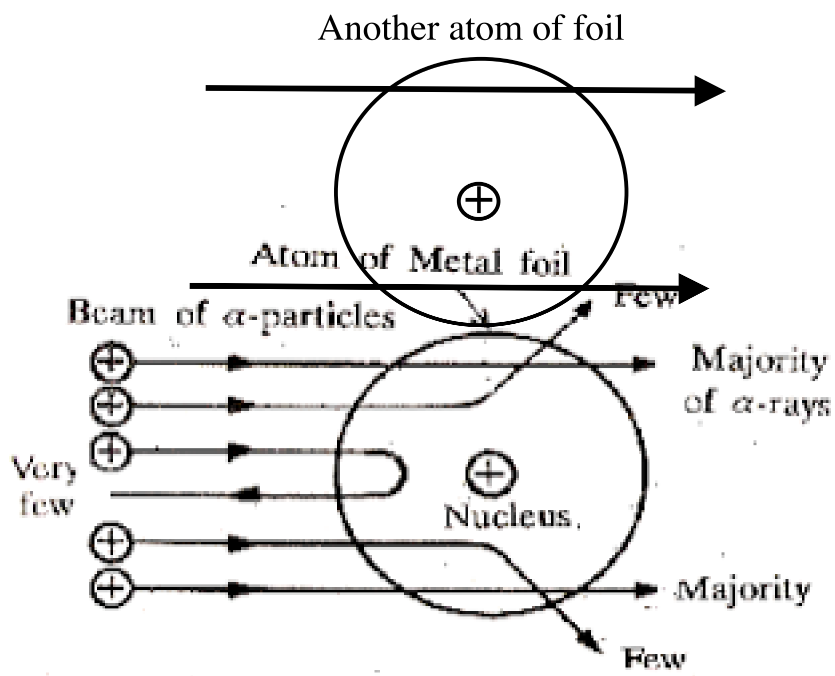
"One day Geiger came to me and said 'Don't you think that young Marsden ought to begin a small research?' Now I had thought that too, so I said, 'Why not let him see if any a particles can be scattered through a large angle?' I may tell you in confidence that I did not believe they would be, since we knew that the a particle was a very fast massive particle , with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings, the chance of an a particle's being scattered backwards was very small. Then I remember two or three days later Geiger coming to me in great excitement and saying 'We have been able to get some of the a particles coming backwards' It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-shell at a piece of tissue paper and it came back and hit you."

"On consideration I realized that this scattering backwards must be the result of a single collision and when I made calculations I saw it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus…"

Rutherford's Gold Foil Experiment



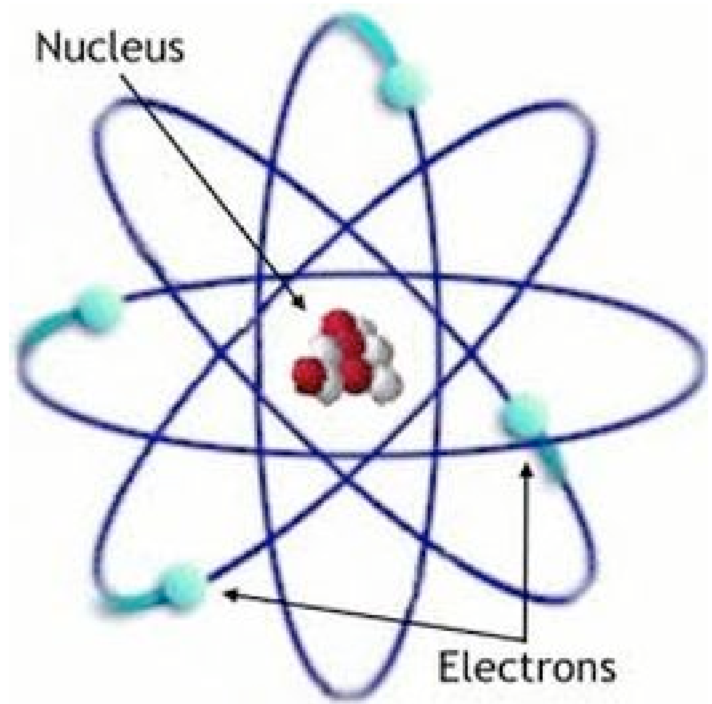
Only a tiny fraction of the particles bounced backwards.

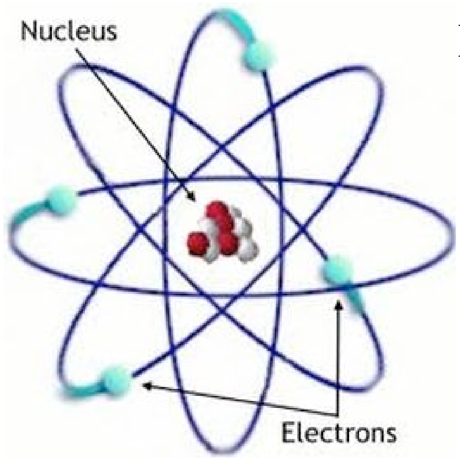


Opposites attract, but like repels like!”

Given this observation, Rutherford proposed a “planetary atom” in which the tiny negative electrons orbited a large positively charged nucleus.

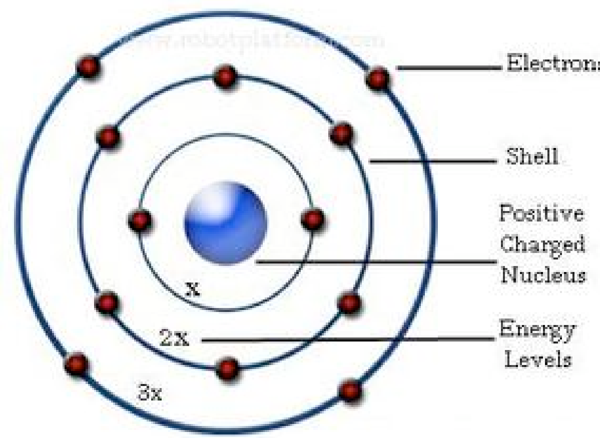
He named the positively charged entities in the nucleus “protons” and concluded there must be similarly “sized” entities without charge (neutrons).

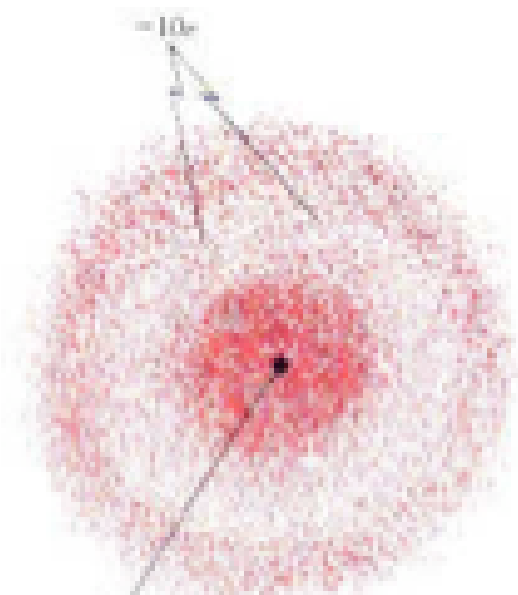




Rutherford (1910)

Bohr (1913)





Schrodinger (1926)

The bus driver story. Nelson, New Zealand.

Radiation and X-rays Have Been Popular with the Nobel Committee

1901 WC Roentgen Discovery of X-rays

1903 H. Becquerel, P. Curie, M. Curie Discovery of radioactivity

1906 JJ Thompson Discovery and characterization of electron

1908 E. Rutherford Discovery and characterization of atomic nucleus.

1911 M. Curie Discovery of radium, polonium.

1914 M. von Laue Diffraction of X-rays

1915 WL and WH Bragg Atomic structure of salt by X-ray diffraction.

1946 H. Muller X-rays cause mutations.