

# The Birth of Modern Physics

1895 - 1910

Thornton and Rex, Ch. 1

1895

ROENTGEN  $\longrightarrow$  X-RAYS

1896

BECQUEREL  $\longrightarrow$  RADIOACTIVITY

1897

THOMSON  $\longrightarrow$  THE ELECTRON

1900

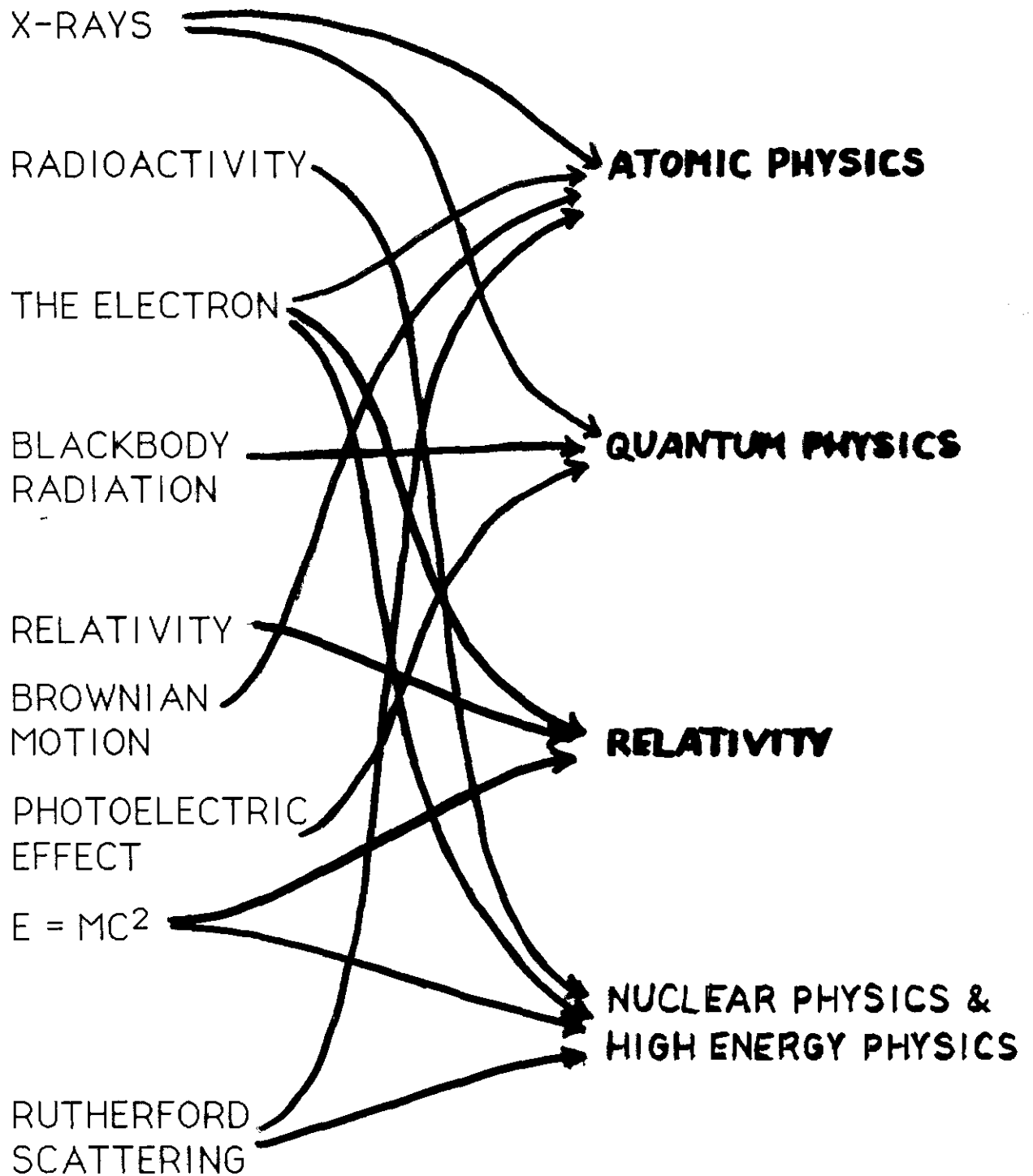
PLANCK  $\longrightarrow$  BLACKBODY  
RADIATION

1905

EINSTEIN  $\begin{cases} \longrightarrow \text{RELATIVITY} \\ \longrightarrow \text{BROWNIAN} \\ \text{MOTION} \\ \longrightarrow \text{PHOTOELECTRIC} \\ \text{EFFECT} \\ \longrightarrow \text{E} = \text{MC}^2 \end{cases}$

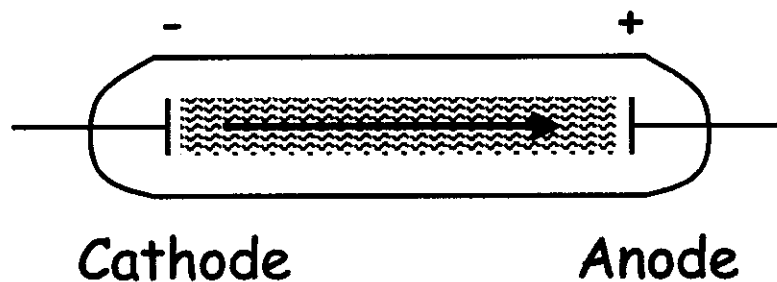
1907

RUTHERFORD  $\longrightarrow$  RUTHERFORD  
SCATTERING



## Important discoveries of 1895-1897 (X-rays, radioactivity, the electron)

- Made while experimenting with cathode ray tubes



- Plucker (1858-1859) - glow moves with a magnet.
- Hittorf (1869) - objects in front of cathode cast shadows
- Goldstein (1876) coins term "cathode rays"

But what *were* cathode rays?

- Electromagnetic waves?

-conclusion of German establishment

(Hertz failed to bend rays with electric field (1892).)

- Electrically-charged particles?

-prevailing view in England

## J.J. Thomson (1856-1940)

- In 1897 he proved conclusively that cathode rays were indeed streams of negatively-charged particles.

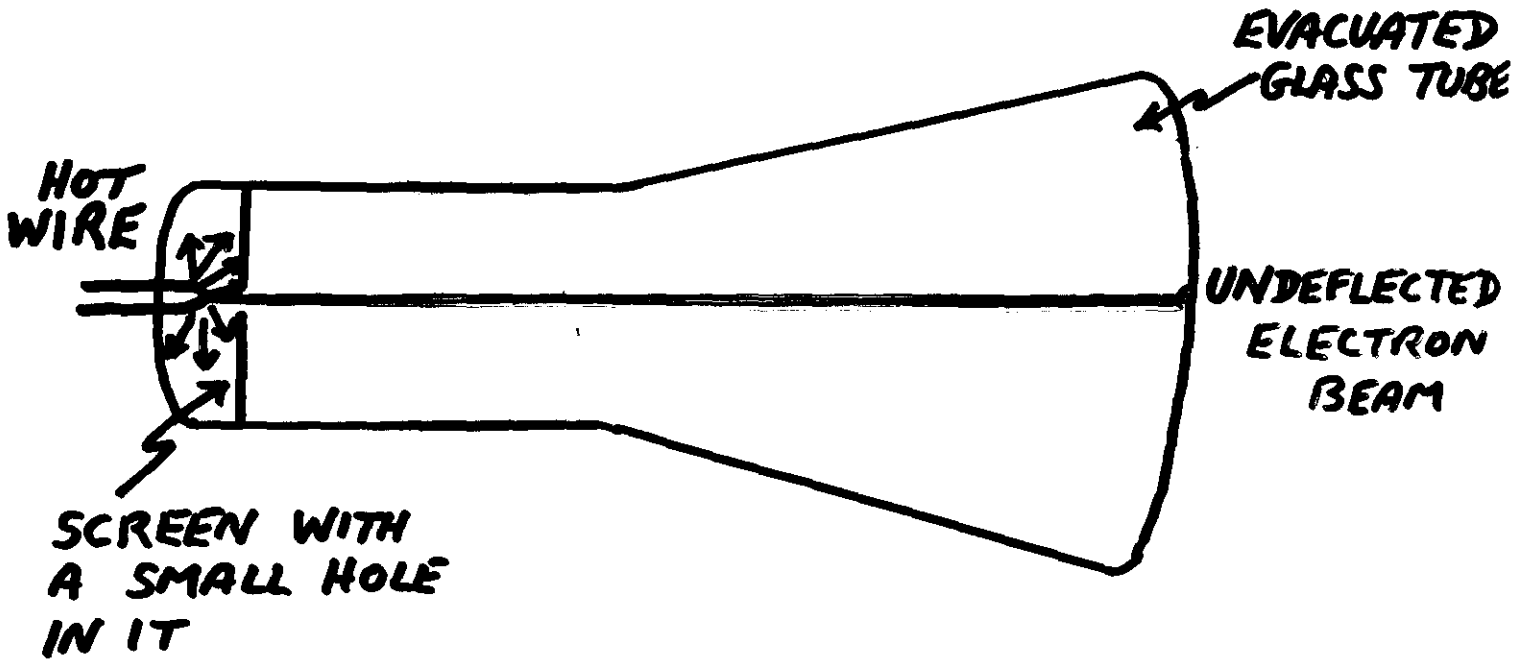
-obtained better vacuum

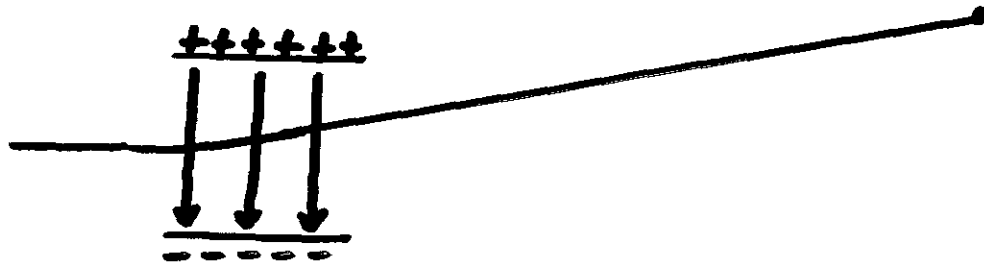
-deflected the rays by both electric and magnetic fields.

-able to calculate

$$\frac{\text{Charge}}{\text{Mass}} = \frac{e}{m} = 1.7 \times 10^{11} \text{ Coulombs/kg}$$

(about 2000 times larger than that of Hydrogen atom)





ADD AN ELECTRIC FIELD POINTING DOWN.  
THIS CAUSES THE ELECTRON BEAM  
(NEGATIVELY CHARGED) TO BE BENT UP.

$$\vec{F} = q\vec{E}$$





ADD A MAGNETIC FIELD POINTING INTO THE PAGE. THIS CAUSES THE ELECTRON BEAM TO BE BENT DOWN.

$$\vec{F} = q \vec{v} \wedge \vec{B}$$

IF BOTH  $E$  AND  $B$  FIELDS ARE APPLIED, AND ADJUSTED SO THAT THE NET EFFECT IS AGAIN AN UNDEFLECTED BEAM,

$$\text{THEN :- } qvB = qE$$

$\therefore$  THE VELOCITY (IN THE X DIRECTION) IS

$$v = v_x = \frac{E}{B}$$

IF THE  $B$  FIELD IS TURNED OFF THEN THE OBSERVED DEFLECTION IS GIVEN BY

$$\tan \theta = \frac{v_y}{v_x} = \frac{a_y t}{v_x} = \frac{qE}{m} \frac{L}{v_x^2}$$

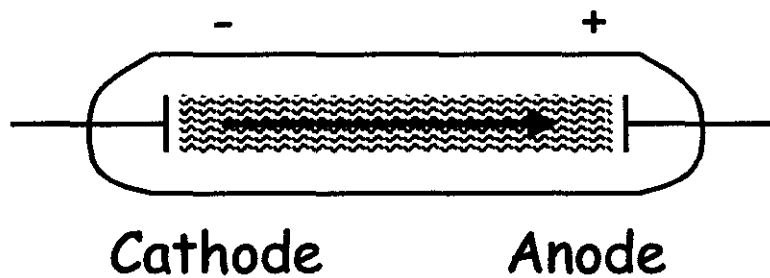
WHERE  $L$  IS THE LENGTH OF THE DEFLECTING PLATE

$$\therefore \frac{q}{m} = v_x^2 \frac{\tan \theta}{EL} = \frac{E^2}{B^2} \frac{\tan \theta}{EL}$$

$$\therefore \frac{q}{m} = \frac{E \tan \theta}{B^2 L}$$

## Explanation of the "glow":

- Electrons striking and exciting residual molecules of air left in the tube (by inferior pumps).



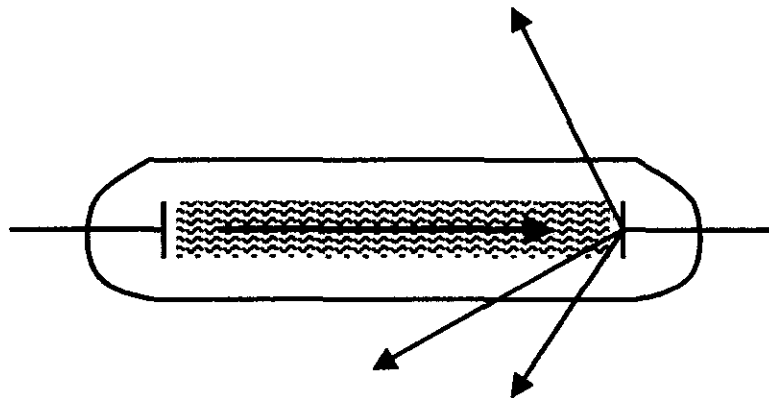
- Thomson (using techniques of Wilson) later measured charge and mass separately.
  - Charges attach on water droplets
- Technique refined by Robert Millikan (1910).

The electron charge is

$$e = -1.6 \times 10^{-19} \text{ Coulombs.}$$

# X-rays

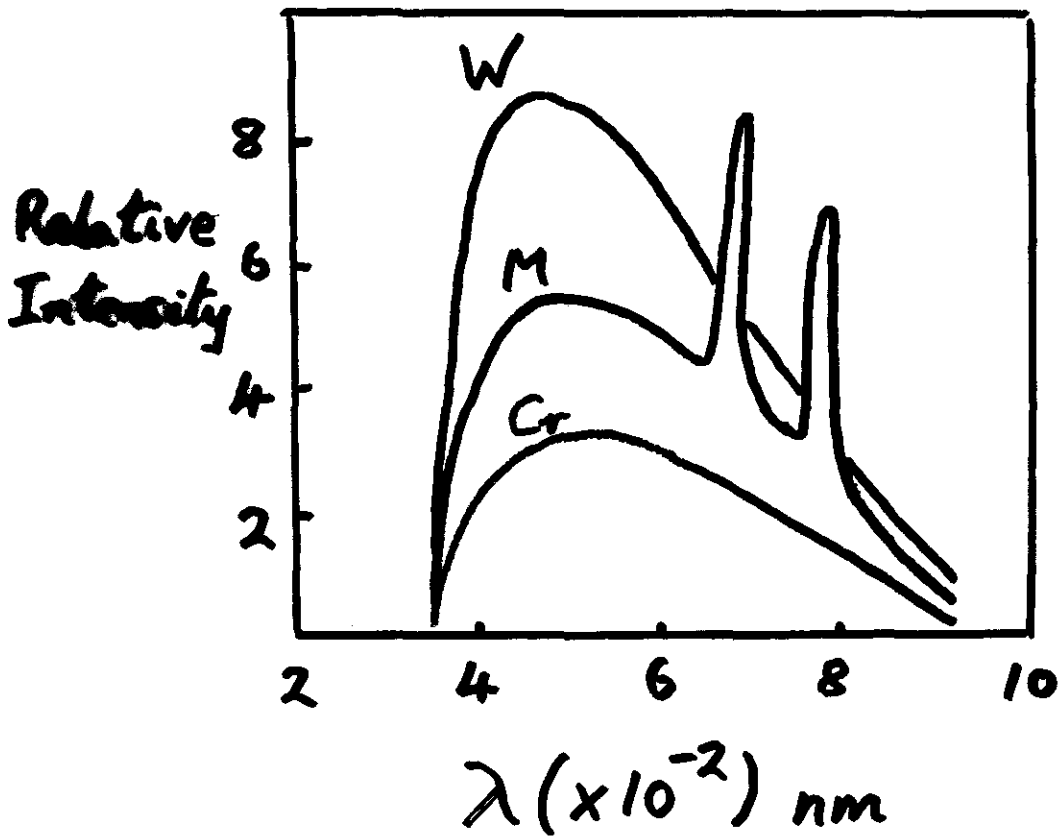
- Roentgen (1895) studying cathode ray tube, noticed glass tubing glowing some distance away.
  - He covered the tube with black paper in a dark room. A fluorescent screen lit up, even if faced away from the discharge tube.
  - Then he placed his hand between the discharge tube and the screen and saw the shadow of his bones!
- ⇒ X-Rays! (later shown to be high frequency electromagnetic waves)



⇒ 1<sup>st</sup> Nobel prize (1901)

## X-Ray Spectra

The wavelength distribution of X-rays produced by bombarding electrons on a high-Z target (fig. 3.17):



(Visible light is  $\sim 400 - 700 \text{ nm}$ )

Sharp peaks: due to atomic excitations at specific frequencies.

Continuum: due to sudden deceleration of electron by heavy nucleus in the anode. The deceleration causes the electron to radiate. Called Bremsstrahlung (German for Braking radiation).

The smallest possible wavelength corresponds to maximum energy loss by the electron (i.e. it loses all of its energy).

$$\lambda_{\min} = \frac{h c}{KE} = \frac{1243 \text{ eV} \cdot \text{nm}}{KE}$$

In a cathode ray tube, the change in potential energy of the electron is  $eV$ , where  $V$  is the voltage difference between cathode and anode.

Thus,  $eV$  is the Kinetic Energy of the electron when it hits the anode.

If all of this energy is converted into a single quantum of X-ray radiation (called a photon), then the photon would have a frequency given by

$$\nu = eV/h, \quad \lambda = c/\nu$$

This is the maximum frequency X-ray that could be emitted in the process.

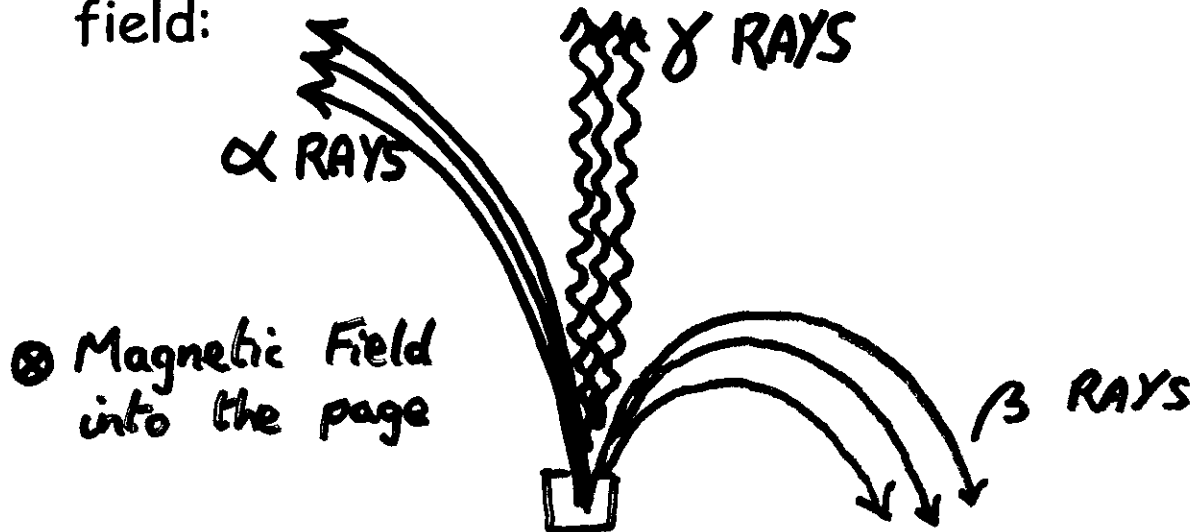
For example,  $2000 \text{ V} \longrightarrow \lambda = 0.621 \text{ nm}$

# Radioactivity

- Becquerel (1896) was testing various fluorescent materials to see if they emitted X-rays.
- He sealed a photographic plate in black paper and sprinkled a layer of Uranyl Potassium sulfate onto the paper.
- He wanted to expose the salt to sunlight in order to make it fluoresce, but that day Paris was gray and overcast.
- Despite this images exposed with great intensity.
- The new phenomenon was named "radioactivity" by Marie Curie.



The radiation from uranium was found to consist of 3 distinct components -- illustrated by its behavior in a magnetic field:



$\beta$ -rays: electrons (Becquerel, 1900). They have a range of energies and are fast and penetrating. Can be absorbed by  $\sim 1$  mm of lead.

$\alpha$ -rays: Helium nuclei (Rutherford, et al). They are heavy, slow, positively-charged particles. Absorbed by  $\sim$  few cm of air.

$\gamma$ -rays: Electromagnetic radiation, with a higher frequency, lower wavelength, even than X-rays.

# Transmutation

Pierre and Marie Curie found new radioactive elements, including Thorium, Polonium, and Radium.

A considerable amount of chemistry detective work, especially by the Curies, Rutherford, and Soddy led to a remarkable conclusion:

Every Radioactive decay is a transmutation of the elements, a change from one element to another.

# MODELS OF THE ATOM

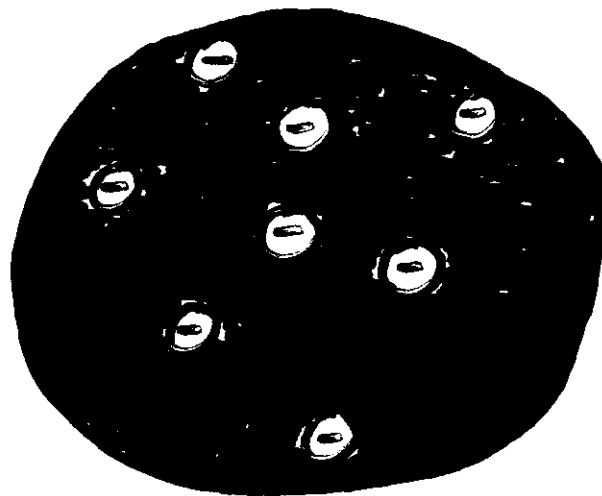
**DURING THE FIRST FEW YEARS OF THE 20<sup>TH</sup> CENTURY, PHYSICISTS WERE OCCUPIED IN DEVISING MODELS OF ATOMS THAT WOULD BE CONSISTENT WITH KNOWN PHYSICAL AND CHEMICAL DATA. SUCH MODELS HAD TO FEATURE:-**

- 1. ELECTRONS AS CONSTITUENTS,**
- 2. SOME POSITIVE CHARGES TO NEUTRALIZE THE NEGATIVE CHARGES OF THE ELECTRONS,**
- 3. SOME SCHEME TO ACCOUNT FOR THE VARIOUS, DIFFERENT ATOMIC WEIGHTS,**
- 4. SOMETHING TO ACCOUNT FOR THE DIFFERENT CHEMICAL PROPERTIES OF ATOMS.**

# THE "PLUM PUDDING" MODEL

IN 1904 J.J. THOMSON DEVELOPED A MODEL OF THE ATOM WHICH CAME TO BE CALLED THE "PLUM PUDDING" MODEL.

IN THIS MODEL, "A NUMBER OF NEGATIVELY-CHARGED CORPUSCLES WERE ENCLOSED IN A SPHERE OF UNIFORM POSITIVE ELECTRIFICATION". THE ATOM WAS IMAGINED TO BE A SPHERICAL BLOB OF POSITIVE "PUDDING" WITH ELECTRON "PLUMS" EMBEDDED IN IT.



THE POSITIVE CHARGE JUST CANCELS OUT THE NEGATIVE CHARGE OF THE ELECTRONS.

# RUTHERFORD SCATTERING

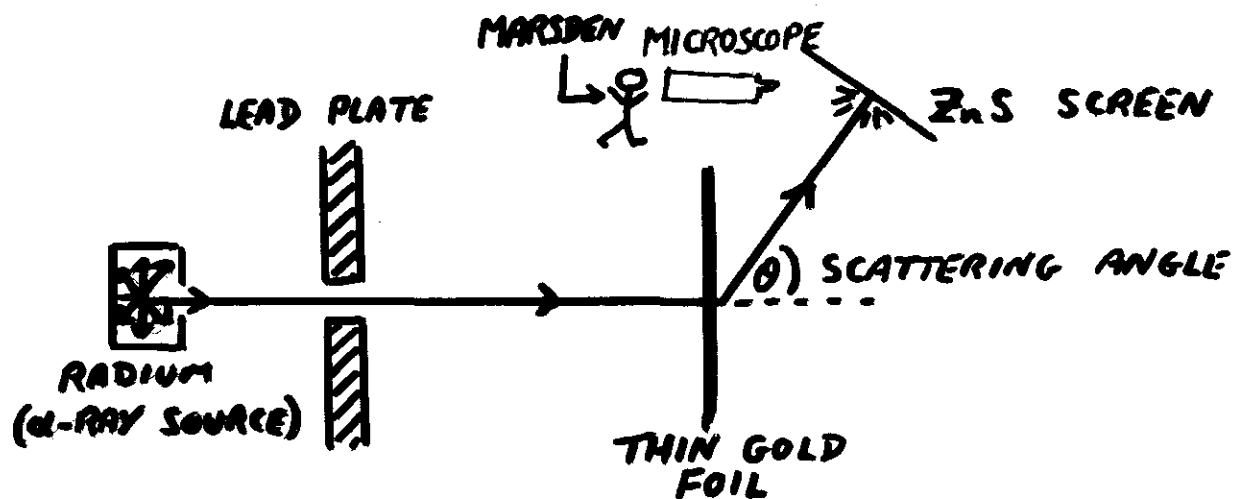
IN 1907 ERNEST RUTHERFORD, A NEW ZEALANDER WHO HAD BEEN WORKING IN CANADA, MOVED BACK TO ENGLAND AS PROFESSOR OF PHYSICS AT MANCHESTER UNIVERSITY.

HE MADE UP A LIST OF POSSIBLE SUBJECTS FOR RESEARCH. NUMBER 7 ON THE LIST WAS "SCATTERING OF  $\alpha$ -RAYS". RUTHERFORD HAD STUDIED  $\alpha$ -RAYS FOR SEVERAL YEARS (CONCLUDING THAT THEY WERE HELIUM ATOMS) AND HAD COME TO APPRECIATE THEIR GREAT VALUE AS ATOMIC PROBES. THEY WERE MUCH MORE MASSIVE THAN THE  $\beta$ -RAYS AND THEY INTERACTED VIGOROUSLY WITH MATTER.

RUTHERFORD WORKED WITH AN EXPERIENCED PHYSICIST HANS GEIGER AS HIS RESEARCH ASSISTANT AND AN 18-YEAR OLD MANCHESTER UNDERGRADUATE, ERNEST MARSDEN, ON THE PROBLEM OF  $\alpha$ -RAY SCATTERING.

IT HAD BEEN SHOWN THAT IT WAS POSSIBLE TO "OBSERVE"  $\alpha$ -RAYS USING A PHENOMENON CALLED SCINTILLATION. IF A SCREEN WAS COATED WITH ZINC SULFIDE (OR SIMILAR) THEN, WHEN AN  $\alpha$ -RAY STRUCK THE SCREEN, IT EMITTED A SHORT AND FAINT FLASH OF LIGHT. IT WAS EXTREMELY TEDIOUS TO DARK-ADAPT AND THEN FOCUS ON A SCREEN TO OBSERVE THE EFFECT OF THE  $\alpha$ -RAYS.

RUTHERFORD, GEIGER AND MARSDEN ASSEMBLED AN EXPERIMENTAL ARRAY THAT LOOKED LIKE:-



**TO THE AMAZEMENT OF RUTHERFORD AND GEIGER, MARSDEN DISCOVERED THAT OFTEN THE  $\alpha$ -RAYS WERE SCATTERED THROUGH VERY LARGE ANGLES. (1 IN 20,000 EVEN BOUNCED BACK IN THE DIRECTION FROM WHICH THEY HAD COME - A SCATTERING ANGLE OF  $180^\circ$ .) IT WAS AN INCREDIBLE RESULT!**

**$\alpha$ -RAYS WHICH WERE HARDLY DEFLECTED BY THE STRONGEST ELECTRICAL FORCES THEN KNOWN COULD BE TURNED AROUND BY A GOLD FOIL ONLY A FEW HUNDREDS OF ATOMS THICK.**

**UNDER RUTHERFORD'S DIRECTION, GEIGER AND MARSDEN PUBLISHED THE RESULTS OF THE EXPERIMENT. RUTHERFORD PONDERED THE MEANING OF THE RESULTS FOR MORE THAN A YEAR.**

LATE IN 1910 WITH THE AID OF A SIMPLE CALCULATION, RUTHERFORD AT LAST SAW THE MEANING OF HIS RESULTS. HE CALCULATED JUST HOW CLOSE TO THE POSITIVE CHARGE OF THE GOLD ATOM THE POSITIVE CHARGE OF THE  $\alpha$ -RAYS COULD GET BEFORE COULOMB'S LAW STOPPED THEM AND REVERSED THEIR DIRECTION. THE CALCULATION SHOWED DISTANCES OF APPROXIMATELY  $1E-14$  m, (ONE TEN-THOUSANDTH OF THE SIZE OF THE ATOM).

THIS MEANS THAT THE POSITIVE CHARGE OF THE ATOM IS FOUND ONLY AT THE VERY CENTER OF THE ATOM, NOT DISTRIBUTED THROUGHOUT THE ATOM AS THOMSON HAD PROPOSED IN HIS PLUM PUDDING MODEL.

RUTHERFORD HAD DISCOVERED THAT ATOMS CONSIST OF A COMPACT POSITIVELY-CHARGED NUCLEUS, AROUND WHICH CIRCULATE THE NEGATIVE ELECTRONS AT A LARGE DISTANCE. THE NUCLEUS OCCUPIES 1/10000 OF THE RADIUS OF THE ATOM OR ONE TRILLIONTH OF THE ATOMIC VOLUME, BUT IT CONTAINS ALMOST ALL OF THE MASS OF THE ATOM.