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5.111 Principles of Chemical Science  
Fall 2008

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## 5.111 Lecture Summary #2

**Readings for today:** A.2-A.3 (pgs F10-F13), B.1-B.2 (pgs F15-F18), and Section 1.1.

**Read for Lecture #3:** Section 1.2 (1.1 in 3<sup>rd</sup> ed) – The Characteristics of Electromagnetic Radiation, Section 1.4 (1.2 in 3<sup>rd</sup> ed)- Radiation, Quanta, and Photons (focus on pgs 10-12 in the 4<sup>th</sup> ed or pgs 5-7 in the 3<sup>rd</sup> ed).

- Topics:**
- I. Discovery of the electron and the nucleus
  - II. (Failure of) the classical description of the atom

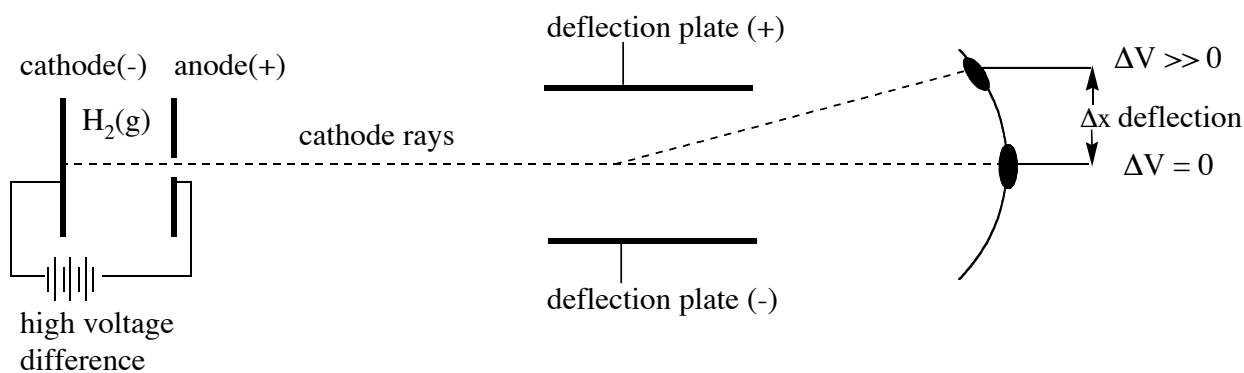
Heading into the **20th century** there was a feeling by many in the chemistry and physics communities that our scientific knowledge was nearly complete. It was universally accepted that atoms were the most basic constituent of matter and that the behavior of *all* matter could be explained through Newtonian mechanics.

**BUT...**several discoveries and observations contradicted these theories:

### I. A) DISCOVERY OF THE ELECTRON

**J.J. Thomson** (English physicist, 1856-1940) in 1897 discovers the electron and determines the charge to mass ratio. In 1906 he wins the Nobel Prize.

The Experiment:



cathode rays = \_\_\_\_\_-charged particles = electrons

If  $\Delta V$  (the voltage difference between the two deflection plates) = 0 there is no deflection, but when  $\Delta V$  is large there is  $\Delta x$  deflection towards the positive plate. From classical electromagnetism, Thompson knew that

$\Delta x_{(-)} \propto$  \_\_\_\_\_  $e_{(-)} =$  \_\_\_\_\_ of the negative particle

$m_{(-)} =$  \_\_\_\_\_ of the negative particle

BUT when a very large  $\Delta V$  is applied a slight deflection towards the negative plate is also observed. Therefore there is also a positive particle!

$$\Delta x_{(+)} \propto \frac{e_{(+)}}{m_{(+)}}$$

$e_{(+)}$  = charge of the positive particle  
 $m_{(+)}$  = mass of the positive particle

BUT  $|\Delta x_{(-)}| \gg \gg |\Delta x_{(+)}|$

Thompson suspected that the positive particle was  $H^+$  and H was the source of the negative particle. Since H is electronically neutral,

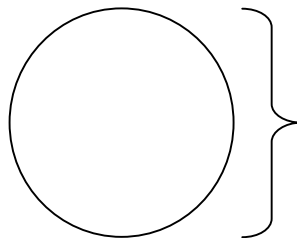
Then  $|e_{(-)}| = |e_{(+)}|$

So:  $\frac{|\Delta x_{(-)}|}{|\Delta x_{(+)}|} = \frac{m_{(+)}}{m_{(-)}}$

Since the ratio of  $\Delta x$  is large the ratio of masses will be large :  $m_{(-)} \ll m_{(+)}$

This negative particle from the cathode ray tubes was named the **electron** ( $m = 9.11 \times 10^{-31}$  kg). Atoms are NOT indivisible!

Thomson proposed a model of the atom in which electrons are embedded in a cloud of positive charge. His (inaccurate) model is often referred to as the "Plum pudding model".



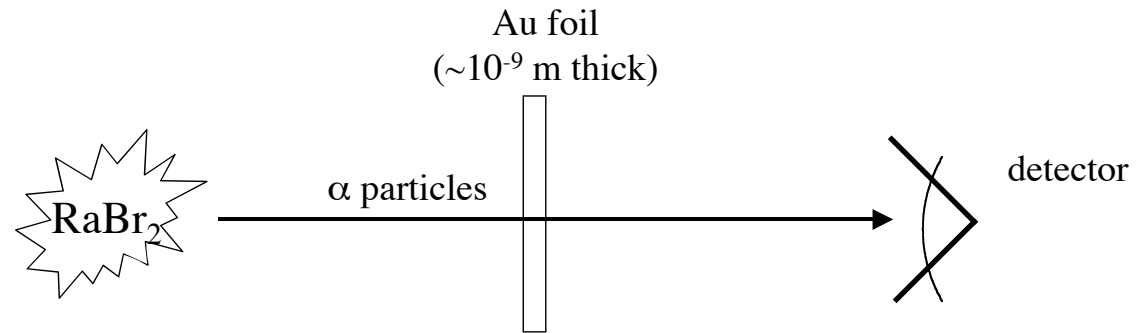
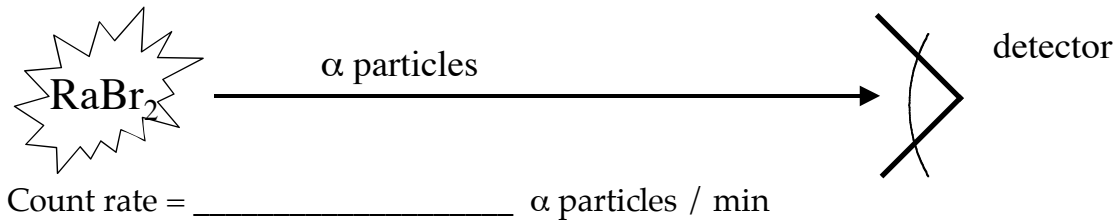
### I. B) DISCOVERY OF THE NUCLEUS

**Ernest Rutherford** (Cambridge University, England, 1871-1937) studied  $\alpha$  emission from newly-discovered radioactive elements.

- $\alpha$  particles were known to be heavy, charged particles
- $\alpha$  particles are \_\_\_\_\_ atoms- this was unknown in 1911

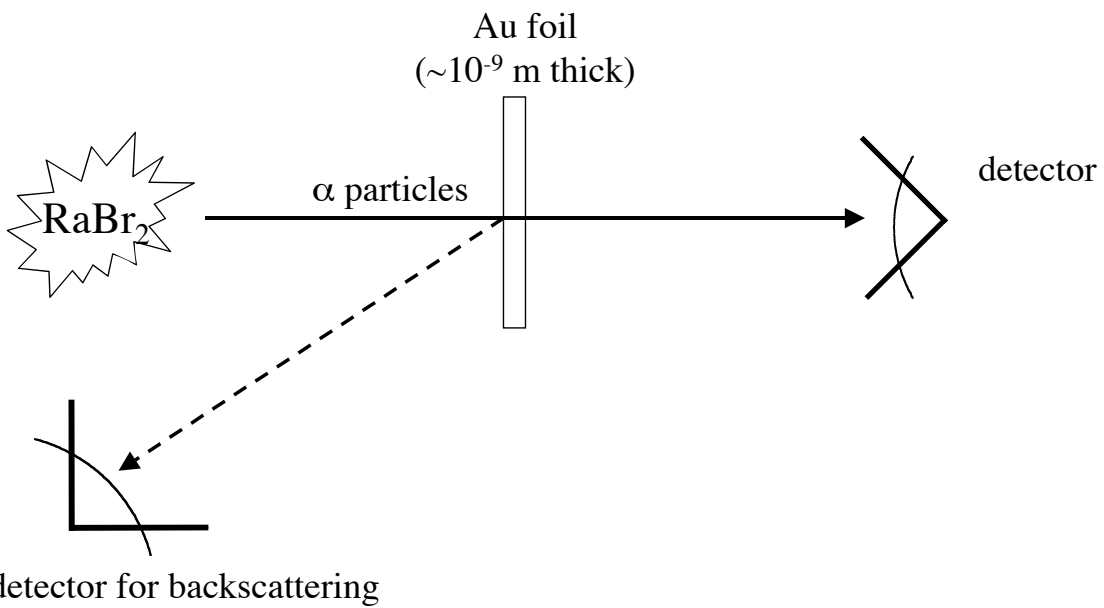
In 1911 Rutherford tested the plum pudding model. (Experiments were done with a postdoc, Hans Geiger, and an undergraduate, E. Marsden.)

The Experiment:



It appeared that all of the  $\alpha$  particles passed through the Au foil.

A detector was built that could swing around to the front side and measure any potential back scattered particles.

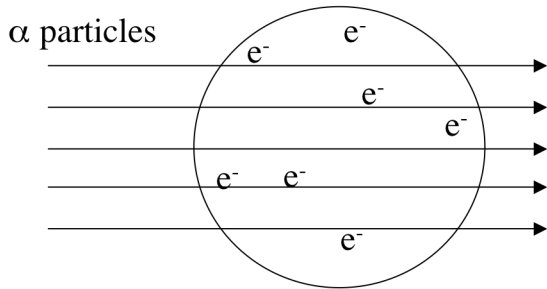


Backscattering was detected!!

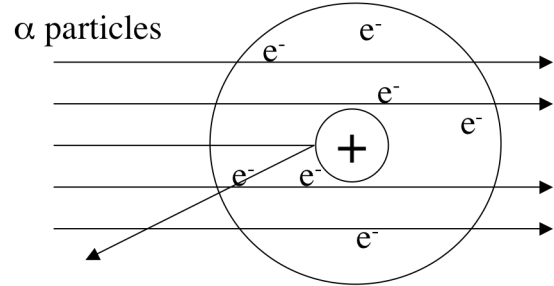
Probability (P) of backscattering:

$$P = \frac{\text{count rate backscattered}}{\text{count rate of incident particles}} = \frac{\quad}{\quad} =$$

Interpretation:



Plum pudding model disproved!



New atomic model

- Since the vast majority of  $\alpha$  particles pass through the Au foil undeflected, **the Au atoms are mostly** \_\_\_\_\_.
- A very tiny percentage of  $\alpha$  particles hit something massive in the atom and backscatter (bounce back). This indicates that **most of the mass of the atom is concentrated in a very small volume relative to the volume of the entire atom**. We now call this the NUCLEUS.
- Rutherford calculated the diameter of the nucleus to be \_\_\_\_\_ m. His calculation (see below) related the probability of backscattering to the diameter of the nucleus based on the size of the atom ( $10^{-10}$  m) and the thickness of the foil.
- Rutherford proposed the charge on the nucleus to be positive, since electrons are negatively charged and atoms are neutral.

$$\text{Charge on the nucleus} = \frac{Ze}{A} \quad \begin{array}{l} Z = \text{atomic number} \\ e = \text{absolute value of electron's charge} \end{array}$$

NOW FOR AN IN-CLASS RUTHERFORD BACKSCATTERING EXPERIMENT!

Please imagine:

white Styrofoam balls = 1 monolayer of Au nuclei

ping pong balls =  $\alpha$  particles

\_\_\_\_\_ = radioactive material emitting  $\alpha$  particles

Probability of backscattering (P) = \_\_\_\_\_

(We will experimentally determine this value.)

P is related to r, the radius of an Au nucleus (styrofoam ball) in the following way:

P = \_\_\_\_\_ = \_\_\_\_\_

P =  $\frac{\text{_____}}{1.39 \text{ m}^2}$

We can solve for r (radius) and d (diameter) of the "Au nucleus" / Styrofoam ball:

r = \_\_\_\_\_                      d = 2r = \_\_\_\_\_

Now we can experimentally find P to determine d, the diameter of the nucleus:

P = \_\_\_\_\_ =                      d = \_\_\_\_\_

## II. (FAILURE OF) THE CLASSICAL DESCRIPTION OF AN ATOM

How is an e<sup>-</sup> bound to the nucleus? What is the force between them? **Electromagnetic force.** We will simplify this by calling it the **Coulomb force.**

So the force between a positively-charge nucleus and a negatively-charged electron is Coulomb force, which can be quantified by **Coulomb's Force Law.**

For a hydrogen atom:

F(r) = \_\_\_\_\_

e = absolute value of an electron's charge  
(note: nuclear charge = +e for a H atom)

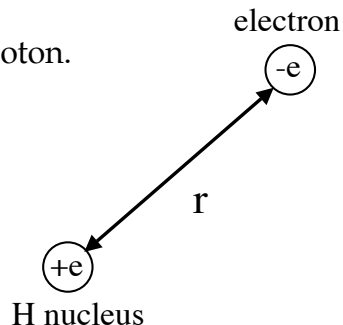
r = distance between two charges

$\epsilon_0$  = permittivity constant of a vacuum  
( $8.854 \times 10^{-12} \text{ C}^2\text{J}^{-1}\text{m}^{-1}$ )

Consider an H atom ( $Z=1$ ) with 1 electron and 1 proton.

When  $r \rightarrow \infty$   $F(r) = \underline{\hspace{2cm}}$

As  $r \rightarrow 0$   $F(r) = \underline{\hspace{2cm}}$



The closer the electron is to the nucleus, the larger the attractive force between the two charges.

- The Coulomb force law tells us the force ( $F$ ) as a function of  $r$ .
- The Coulomb force law does not tell us how  $r$  changes with  $\underline{\hspace{2cm}}$ .

There is a **CLASSICAL EQUATION OF MOTION** that tells us how the electron and nucleus move under influence of this Coulomb force: Newton's 2<sup>nd</sup> Law

$$F = ma \qquad \text{Force} = \text{mass times acceleration}$$

We can rewrite  $F$  as a function of velocity,  $F = m(\underline{\hspace{2cm}})$  or distance,  $F = m(d^2r/dt^2)$

We can plug in the Coulomb force law for  $F$ , and solve the equation for a given initial value of  $r$ .

If  $r_{\text{initial}}$  is  $10 \text{ \AA}$  ( $10^{-10} \text{ m}$ ), a typical distance for an H atom, the calculation indicates that

$$r = 0 \text{ at } t = \underline{\hspace{2cm}} \text{ sec!}$$

**This predicts that the electron should plummet into the nucleus in  $\underline{\hspace{2cm}}$ !**

What is wrong here?

It turns out that the **laws of classical mechanics** no longer work at this size scale.

Need a new kind of mechanics to describe this and other "unsettling" observations.

**QUANTUM MECHANICS** provides a single and comprehensive theory that explains the behavior of matter on an atomic (nanometer or smaller) scale.