5.111 Lecture Summary #2 Friday, September 5, 2014

Readings for today: Sections A.2-A.3 (5^{th} *ed* pgs F9-13, 4^{th} *ed* pgs F10-13) – Force and Energy, Sections B.1-B.2 (5^{th} *ed* pgs F15-17, 4^{th} *ed* pgs F15-18) – Elements and Atoms , Section 1.1 (5^{th} *ed* and 4^{th} *ed* pgs 1-3) – The Nuclear Atom.
Read for Lecture #3: Section 1.2 – The Characteristics of Electromagnetic Radiation, Section 1.4 – Radiation, Quanta, and Photons (focus on pgs 10-12 in the 5^{th} or 4^{th} *ed*).

Topics: **I.** Discovery of the electron and the nucleus
II. (Failure of) the classical description atoms/intro to quantum mechanics

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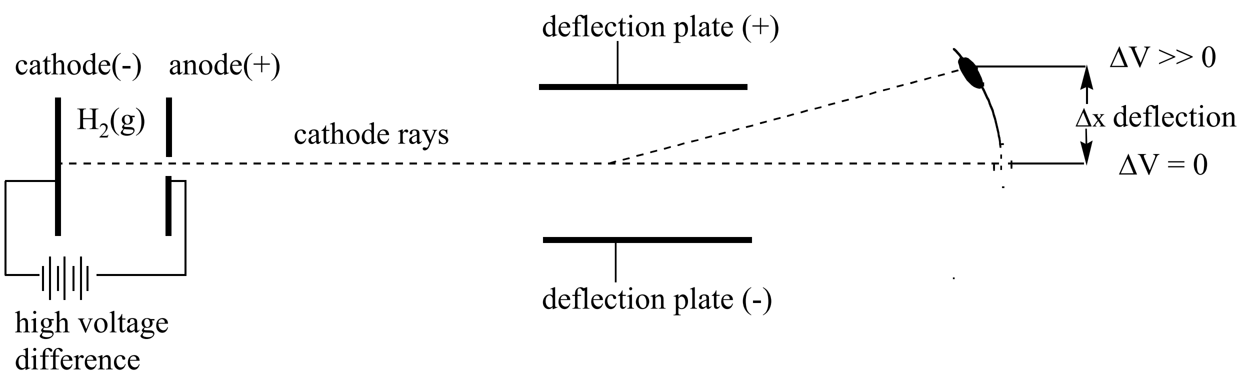
I. A) DISCOVERY OF THE ELECTRON

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:



If ΔV (the voltage difference between the two deflection plates) = 0 there is no deflection, but when ΔV is >> 0, there is Δx deflection towards the positive plate.

cathode rays = ______________ charged particles = electrons

From classical electromagnetism, Thompson knew that

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

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

Then Thomson applied a very large ΔV and a *slight* deflection towards the negative plate was observed. Therefore there is also a positively charged particle!

$\Delta x_{(+)} \propto$ ________ $e_{(+)}$= charge of the positive particle

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

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

Since H is electronically neutral,

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

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

Since the ratio of Δx is large, the ratio of masses will be large: $m_{(-)}$ ___________ $m_{(+)}$

This negative particle from the cathode ray tubes was later named the **electron** and its mass was later determined to be very small ($m = 9.11 \times 10^{-31}$ kg).

Atoms are NOT indivisible!

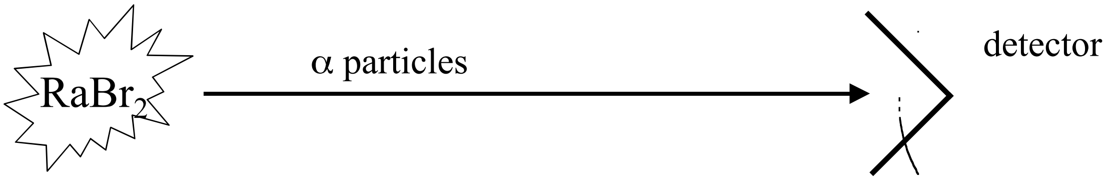
I. B) DISCOVERY OF THE NUCLEUS

Ernest Rutherford (Cambridge University, England, 1871-1937) studied α emission from newly-discovered radioactive elements that he got from his friend Marie Curie.

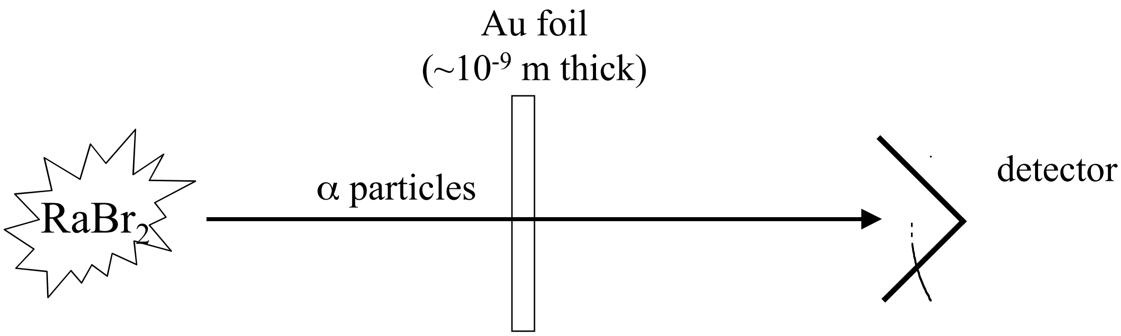
- $RaBr_2$ gave off α particles
- α particles are ________ ions. This information was unknown in 1911.

In 1911, Rutherford experimented with this new radioactive material and discovered the nucleus. (Experiments were done with a postdoc, Hans Geiger, and an undergraduate, E. Marsden.)

The Experiment:



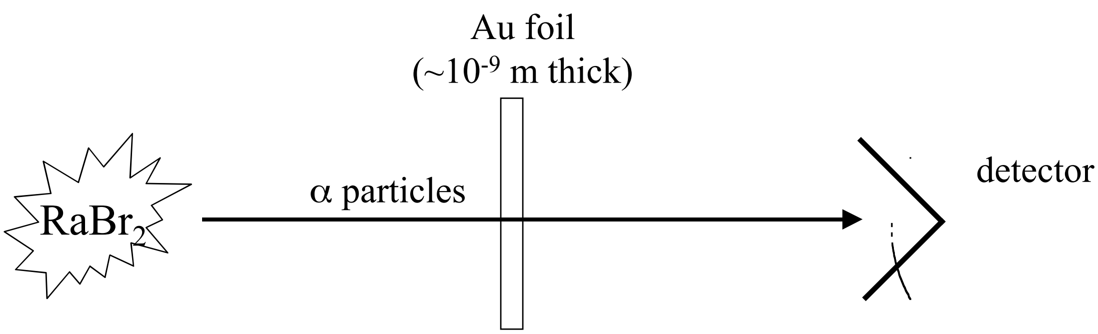
Count rate = ____________________ α particles / min

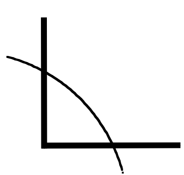


Count rate = ____________________ α particles / min

It appeared that all of the α 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.





detector for backscattering

Count rate = ____________________ α particles / min

Backscattering was detected!!

Probability (P) of backscattering:

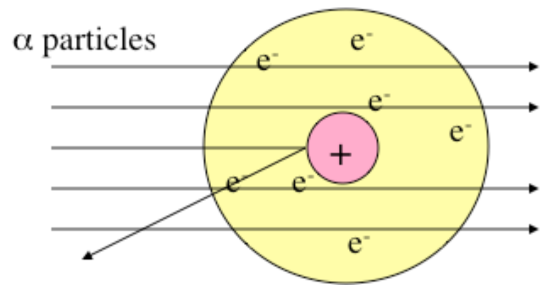
$$P = \frac{\text{count rate backscattered}}{\text{count rate of incident particles}} = \_\_\_\_\_\_\_\_\_\_ =$$

Interpretation:

- Since the vast majority of α particles pass through the Au foil undeflected, **the Au atoms are mostly ______________** .

- A very tiny percentage of α particles hit something massive in the atom and backscatter (bounce back). This observation 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.

- New model for α particles



- Rutherford proposed the charge on the nucleus to be positive, since electrons are negatively charged and atoms are neutral.

  Charge of the electrons in an atom = - Ze
  Z = atomic number
  e = absolute value of electron's charge

  Charge of the nucleus of an atom = __________

- Rutherford calculated the diameter of the nucleus to be 10^{-14} m. His calculation (see below) related the probability of backscattering to the diameter of the nucleus based on the size of the atom and the thickness of the foil.

NOW FOR AN IN-CLASS RUTHERFORD BACKSCATTERING EXPERIMENT THAT WAS DESIGNED BY PROFESSOR SYLVIA CEYER.

Please imagine:

white Styrofoam balls = 1 monolayer of Au nuclei

ping pong balls = α particles

you = radioactive material emitting α 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 = ____________

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 =

(Actual diameter of Styrofoam ball is 2.5 cm)

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

How is an electron bound to the nucleus? What is the force between them? **Coulomb's Force Law** describes the force of attraction and repulsion between charged particles.

Coulomb Force (F_r) = $\frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$

Q_x = charge on particle x

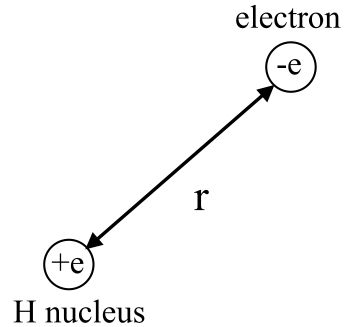
r = distance between two charges

$\boldsymbol{\varepsilon_0}$ = permittivity constant of a vacuum ($8.854 \times 10^{-12}\ C^2J^{-1}m^{-1}$)

When charges are the same sign, acceleration of the particles will push them apart. The force is positive and repulsive.

When charges are the opposite sign, acceleration will pull them together. The force is _______________and attractive.

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



When $r \to \infty$ F(r) = ______________

As $r \to 0$ F(r) = ______________

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 _________________.

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^{nd} Law

F = ma Force = mass times acceleration

We can rewrite F as a function of velocity, $F = m(dv/dt)$ 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 $r_{initial}$ is 0.5 Å (0.5×10^{-10} m), a typical distance for an H atom, the calculation indicates that

r = 0 at t = ____________ sec!

This predicts that the electron should plummet into the nucleus in ____________ !

What is wrong here?

It turns out that the **laws of classical mechanics** no longer work at this size scale.
A new kind of mechanics was needed 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.