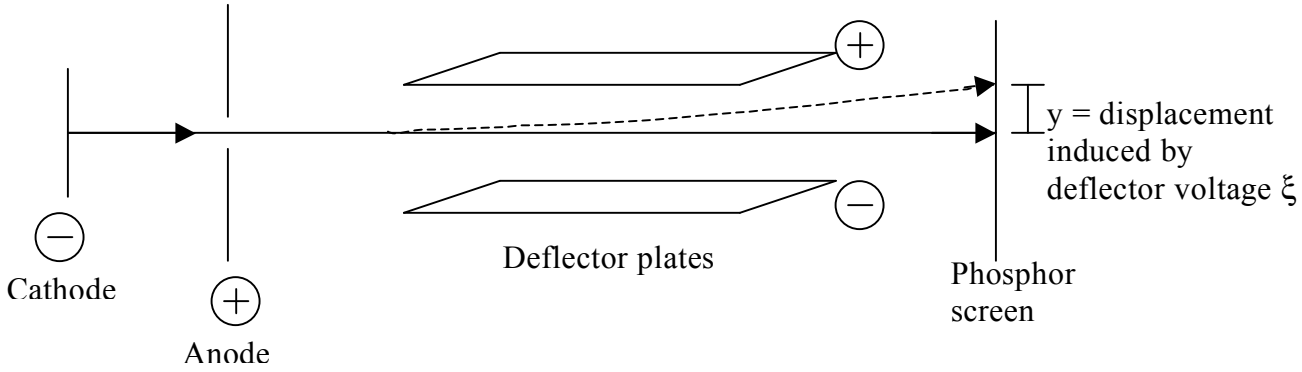
The DEMISE of CLASSICAL PHYSICS

(a) Discovery of the Electron

In 1897 J.J. Thomson discovers the electron and measures $\left(e/m_e\right)$
(and inadvertently invents the cathode ray (TV) tube)

Faraday (1860's – 1870's) had already shown using electrochemistry that amounts of electric current proportional to amounts of some substances could be liberated in an electrolytic cell. The term "electron" was suggested as a natural "unit" of electricity.

But Thomson experimentally observes electrons as particles with charge & mass.



Thomson found that results are independent of (1) cathode material
(2) residual gas composition

⇒ "electron" is a distinct particle, present in all materials!

Classical mechanics ⇒ force on electron due to deflector voltage:

$F_y = \xi e$ (force starts at time $t = 0$ when electron enters region between plates)

$$= m\frac{dv_y}{dt} \qquad \left(F = ma\right) \qquad \therefore \quad \frac{dv_y}{dt} = \xi\left(\frac{e}{m_e}\right)$$

$$\text{Integrating} \;\Rightarrow\; v_y = \left(\frac{e}{m_e}\right)\xi t \qquad \left[\text{Note } v_y\left(t = 0\right) = 0\right]$$

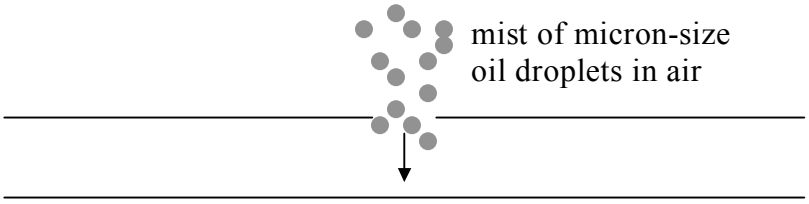
Integrating again since $v_y = \frac{dy}{dt}$ and $y(t=0) = 0 \Rightarrow y = \left(\frac{e}{m_e}\right)\frac{\xi t_f^2}{2}$

$t_f =$ total time electron is between the plates (easily calculated)

Set voltage ξ, calculate time t_f, measure displacement $y \Rightarrow \left(\frac{e}{m_e}\right) = 1x10^{11}$ C/kg

Modern day value is $\left(\frac{e}{m_e}\right) = 1.758x10^{11}$ C/kg

(b) 1909 Milliken oil drop experiment determines *e*, m_e separately



Gravitational force downward:

$F_g = -Mg$ $M =$ mass of droplet, $g =$ gravitational constant

Frictional force upward due to air:

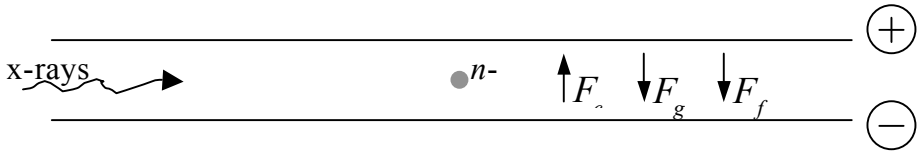
$F_f = 6\pi r\eta v$ $r =$ radius of droplet, $\eta =$ air viscosity, $v =$ droplet velocity

Since $F_f \propto v$, terminal velocity v_t is reached when forces balance

$6\pi r\eta v_t = Mg \Rightarrow$ get droplet mass $M = 6\pi r\eta v_t / g$

Now use x-rays or γ-rays to add some charge (ne) to the droplets

Voltage ξ across plates exerts Coulomb force $F_c = \xi ne$ on the charged droplet



Adjust voltage until drop stops falling: $v = 0 \Rightarrow F_f = 0, \quad F_c = F_g$

$$\xi ne = Mg \qquad \text{Determine } ne = Mg/\xi$$

Mulliken did this for lots of droplets $i = 1,2,3,...$

They all had different charges $(n_i e)$ but all integer multiples of charge (e)

Determined *elementary charge* as $e = 1.59x10^{-19}$ C

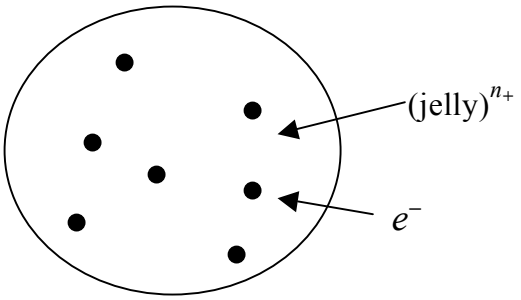
(very close to today's value $e = 1.602x10^{-19}$ C)

Combining values for (e/m_e) and (e) $\Rightarrow$ $\boxed{m_e = 9.11x10^{-31} \text{ kg}}$

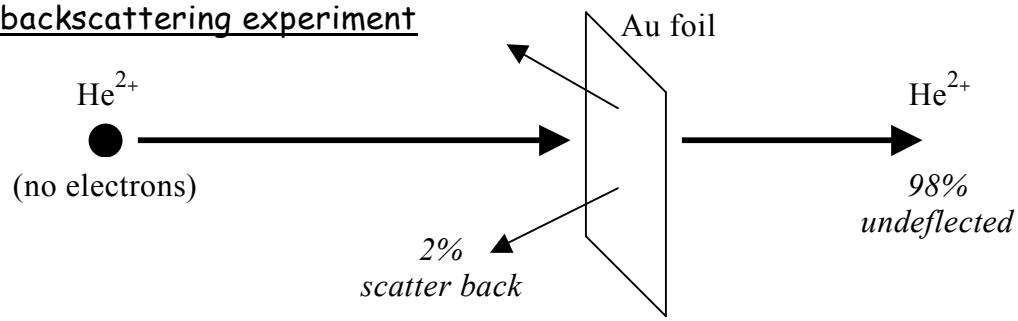
Hydrogen mass was known: $m_H = 1.66x10^{-27}$ kg $\Rightarrow$ *electron is subatomic*!!

(c) <u>Where are the electrons?</u> What's the <u>structure</u> of the atom?

Angstrom (10^{-10} m) atomic size scale already inferred from gas kinetics
First "jellium" model didn't last long

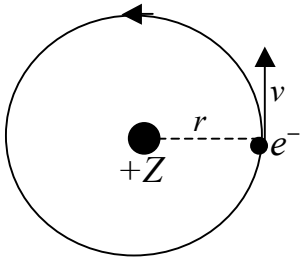


<u>Rutherford backscattering experiment</u>



$\Rightarrow$ (1) He^{2+} nucleus *very* small, << 10^{-10} m (Rutherford estimated 10^{-14} m)
(2) Au atoms are mostly empty!

Rutherford planetary model: classical mechanical model of atomic structure
Coulomb attraction plays the role of gravity



centripetal force $F_c = \frac{m_e v^2}{r}$

Coulomb force $F_C = \frac{Ze^2}{4\pi\varepsilon_0 r^2}$

for stable orbit $\frac{m_e v^2}{r} = \frac{Ze^2}{4\pi\varepsilon_0 r^2} \quad \Rightarrow \quad r = \frac{Ze^2}{4\pi\varepsilon_0 m_e v^2}$

This is stable compared to separated electron & nucleus

$$E = \text{K.E.} + \text{P.E.} = \frac{1}{2} m_e v^2 + \left(-\frac{Ze^2}{4\pi\varepsilon_0 r} \right) = -\frac{1}{2} \frac{Ze^2}{4\pi\varepsilon_0 r} < 0$$

BUT model not consistent with classical electrodynamics:

Accelerating charge emits radiation! (centripetal acceleration = v^2/r)
And since light has energy, E must be getting more negative with time

$\Rightarrow$ r must be getting smaller with time!
$\Rightarrow$ *Electron spirals into nucleus in ~ 10^{-10} s !*

Also, as r decreases, v should increase
Frequency ν of emitted light = frequency of rotation

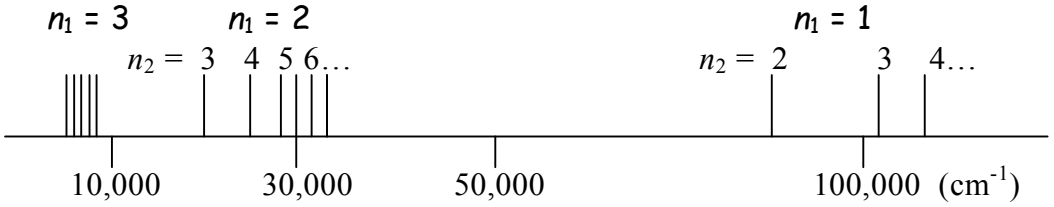
$$\nu \text{ (Hz = cycles/s)} = \frac{v \text{ (m/s)}}{2\pi r \text{ (m/cycle)}}$$

circumference of orbit

$\Rightarrow$ atom should emit light at <u>all</u> frequencies – that is it should produce a <u>continuous</u> spectrum

BUT emission from atoms was known to be discrete, not continuous!

For H:



For the H atom, Rydberg showed that the spectrum was consistent with the simple formula:

$$\bar{\nu}\ (\text{cm}^{-1}) = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

with $n_1 = 1, 2, 3, \ldots$ and $n_2 = n_1 + 1, n_1 + 2, n_1 + 3, \ldots$

$R = 1.097x10^5\ \text{cm}^{-1}$ (Rydberg constant)

n_1 = 1 Lyman series
n_1 = 2 Balmer series
n_1 = 3 Paschen series

visible & UV lines well known

Summary: Rutherford's model of the atom

(1) Is not stable relative to collapse of electron into nucleus
(2) Does not yield discrete emission lines,
(3) Does not explain the Rydberg formula