Electrons and X-Rays

Wilhelm C. Roentgen
1845-1923
Nobel Prize 1901
Discovered X-Rays

Joseph J. Thomson
1856 - 1940
Nobel Prize 1906
Discovered the Electron
Nature of the cathode rays: the discovery of the electron

- **J.J. Thomson** 1856-1940  Nobel Prize 1906
  - Manages to show conclusively that cathode rays are deflected by electric and magnetic fields; do not depend on the material the cathode or the anode is made of
  - Have a negative charge, cathode rays are particles
  - Measures e/m ratio, close (about 35% off) to the present value of $1.76 \times 10^{11} \text{C/kg}$

  $\rightarrow$ Better vacuum available after progress by Crookes
Measurement of the q/m ratio

• An electron moving through the electric field is accelerated by a force: \( F_y = ma_y = qE \)

• Electron angle of deflection: \( \tan \theta = \frac{v_y}{v_x} = \frac{a_y t}{v_0} = \frac{qE \ell}{m v_0^2} \)

• The magnetic field deflects the electron against the electric field force.
  \( \vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = 0 \)

• The magnetic field is adjusted until the net force is zero.
  \( \vec{E} = -\vec{v} \times \vec{B} \)
  \( v = \frac{\vec{E}}{\vec{B}} = v_0 \)

• Charge to mass ratio:
  \[
  \frac{q}{m} = \frac{v_0^2 \tan \theta}{E \ell} = \frac{E \tan \theta}{B^2 \ell}
  \]
q/m ratio results surprising
1000 x larger than q/m for charged hydrogen!

Thomson presented three hypotheses about cathode rays based on his 1897 experiments:
1. Cathode rays are charged particles (which he called "corpuscles").
2. These corpuscles are constituents of the atom.
3. These corpuscles are the only constituents of the atom.

For More Information see AIP history of physics: Discovery of Electron
http://www.aip.org/history/electron/
300 Volts
KE=300 eV

50 V
(1 CM)

L=3 CM
What would a geek do with something like this?
What would a geek do with something like this?

Turn the oscilloscope into a clock.

How???
What would a geek do with something like this?

oscilloscope clock

Scope with X vs Y mode
Connect
Programmable
Microprocessor

Vary Voltages
CH1 (X) CH2 (Y)

Deflect the cathode rays! (electrons)

Write a clock to the screen

Google
“oscilloscope clocks”
2008: Electron Accelerator Clock with sub microsecond accuracy!

http://www.techfresh.net/old-fashioned-cathode-ray-tube-clock/
One of the first computers
With graphics display
~1975 Tektronix 4051

Display: 11” CRT
Processor: Motorola 6800 8 bit
Memory: 32K RAM
Language: BASIC

“Just $6995. Less than most comparable alphanumeric only systems”
**Electron Discovery**

Know for some time that if you took an evacuated tube with 2 electrodes 
apply voltage 
see a glowing (mysterious) 
What was it? Known since early 1800's 
Given the name of "CATHODE RAYS" 
Since there was no model of the atom and no fundamental particles had been discovered, explaining this glow was difficult!

Atoms were generally believed to be the smallest constituent of the matter

J. J. Thompson (Nobel Prize 1906) 
is credited with figuring out this puzzle of the mysterious "cathode rays"

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**Diagram**

- **Cathode** (C-)
- **Heater**
- **Evacuated Tube**
- **Anode** (+)
- **"K-Rays"**

(show demo)
Demo Questions

1) What polarity?

2) Charged or neutral? How tell?

3) What is this device

4) What is the of e-

5) How fast are they traveling? (How to calculate this?)
4) \( KE = eV \)
   \[ \uparrow \quad \text{voltage applied} \]
   \[ \uparrow \quad \text{charge of electron} \]
   \[ = 800 \text{ eV in our case} \]

5) how fast?

\[ KE = mc^2(\gamma - 1) \]
\[ = mc^2 \left( \frac{1}{\sqrt{1-\beta^2}} - 1 \right) \quad \beta \ll 1 \quad \text{why?} \]

Recall first order Taylor Series expansion is
\[ (1 + \alpha)^n \approx 1 + n\alpha \]
\[ n = -\frac{1}{2} \quad \alpha = -\beta^2 \Rightarrow 1 + \left( -\frac{1}{2} \right)(-\beta^2) \]
\[ 1 + \beta^2 \]

So \( KE = mc^2 \left( 1 + \frac{\beta^2}{2} - 1 \right) = \frac{1}{2}mc^2\beta^2 \)

\[ \sqrt{\frac{KE}{mc^2}} = \beta = \sqrt{\frac{800 \text{ eV} \cdot 2}{511000 \text{ eV} \cdot c^2}} = 0.034 \]

or \( v \approx \frac{\gamma}{\beta} c \)
\[ = 3.4 \times 10^{-2} \times 3 \times 10^9 \text{ m/s} \times \frac{1 \text{ km}}{10^3 \text{ m}} \]
\[ = 121000 \text{ km/s} \]
note a easy way to figure out if SR is needed given \( \gamma \), \( m_0 

\begin{align*}
E &= \frac{m_0 c^2 \gamma}{1} \\
\frac{E_{TOT}}{m_0 c^2} &= \gamma \\
\gamma &= \frac{\sqrt{1 + \frac{m_0 c^2}{E_{KE} + m_0 c^2}}}{m_0 c^2}
\end{align*}

if \( \gamma \) close to 1, don't need to use S.R.

note \( KE \ll m_0 c^2 \) in this case

\( \frac{400 \text{eV}}{\gamma E} \ll 51,000 \text{eV} \)
Also possible to measure the charge to mass ratio \( q/m \) of e⁻:

1. \[
\begin{align*}
\text{e}^- & \rightarrow \text{e}^- \\
\text{V}_0 & \rightarrow \text{E} \quad \text{(Down)} \\
\theta & \rightarrow \text{L} \\
\end{align*}
\]

2. \[
\tan \theta = \frac{V_y}{V_x} \\
V_x = V_0 \\
V_y = at \quad t = \frac{L}{V_0}
\]

\[a_y = \frac{qE}{mc} \]

\[
= \frac{\frac{qE}{mc} \frac{L}{V_0}}{V_0} = \frac{9EL}{mcV_0^2} = \tan \theta
\]

so if you measure \( V_0, \theta, E, L \) you can find \( q/mc \)
We can estimate the charge/mass ratio of the electron using this device.

\[ \tan \theta = \frac{q E L}{m_e V_0^2} \]

\[ \frac{V_0^2 \tan \theta}{E L} = \frac{q}{m_e} \]

\[ V_0 = 10,000,000 \text{ m/s (}10^7 \text{ m/s)} \]
\[ E = 50 \text{ V/}10^{-2} \text{ m about 1 cm between plates} \]
\[ L = 3 \text{ cm} \]
\[ \theta = 15^\circ \text{ for 50 V (about)} \]

So plug in numbers:

\[ \frac{(10^7 \text{ m/s})^2 \tan(15^\circ)}{(50 \text{ V)/(10^{-2} m}) (3\times10^{-2} \text{ m})} = \frac{10^{14} \text{ m}^2/\text{s}^2 (0.268)}{150 \text{ V}} \]

\[ = 1.8 \times 10^{-11} \text{ m}^2/\text{s}^2 \text{ which is } \frac{\text{Coulombs}}{\text{kg}} \]

Look up #

\[ \frac{q}{m_e} \text{ electron} = 1.6 \times 10^{-19} \text{ Coulomb} \]

\[ = 9.1 \times 10^{-31} \text{ kg} \]

\[ = 1.76 \times 10^{-11} \text{ Coulombs/kg} \]
But we assumed we had a $e^-$ and knew $m_e$ (to calculate $V_0$).

How to do measurement with no knowledge of the particle, i.e., without knowing $V_0$?

$\Rightarrow$ APPLY $B$ field, $\perp$ to $E$.

ADJUST $|B|$ so it cancels force due to $E$.
(Observe $v$ is no deflection.)

\[
\vec{F} = q\vec{E} \times \vec{v} \times \vec{B} = 0 \Rightarrow \text{no deflection}
\]

\[
\vec{E} = -\vec{v} \times \vec{B}
\]

For $E \perp V \perp B$,

\[
E = V_0 B
\]

$\Rightarrow \frac{E}{B} = V_0$ (GIVES A MEASURE OF $V_0$) if $E, B$ are measured.

Sub $B$ into $A$ and $\tan \theta = \frac{qEL}{m_e V_0^2}$.

Then turn off $B$, measure $\theta$ and can use $\tan \theta = \frac{qEL}{m_e V_0^2}$.

and find $\frac{q}{m_e}$ with only knowing $E, \theta, B, L$. 

\[
\tan \theta = \frac{g}{m} \frac{EL}{B^2L} \frac{IB \vert B \vert^2}{E \vert E \vert^2}
\]

\[
\tan \theta \frac{E}{B^2L} = \frac{g_e}{m_e}
\]

what was the surprise?

\(\frac{g}{m}\) is a big #!

had been measured for \(H^+\) (diatomic)

\(~ 1000\) larger than \(\frac{g}{m}\) for \(H^+\)

\(\Rightarrow\) STUFF (MATTER IS NEUTRAL)

if \(e, H^+\) have same (opposite) charge magnitude

\(\Rightarrow e^-\) is very light!"