TOP HAT

*Top Hat*
*The "join code" is 08724*
*To participate in the cell phone polling,*
*Text to (315) 636 -0905 the four digit code for each*
*question followed by the response.*

Which of the following best describes you?
a.) math teacher
b.) physics teacher
c.) science teacher (not-physics)
d.) technology teacher
e.) other

Discovering the Subatomic World          1

# Discovering the Subatomic World

## Dr. Kurt Fletcher
SUNY Distinguished Teaching Professor
## SUNY Geneseo

## NYS Master Teacher Program
## March 2016

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# Minicourse Outline

**1.) The electron**

2.) The atomic nucleus

3.) and Beyond!

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# Our Approach

- How do we know what we know?

- More experimental than theoretical

- Somewhat historical

- Engage in active learning!

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Things we know about the electron

1.) It's "elementary"

2.) $q = -1.6 \times 10^{-19}\ C$
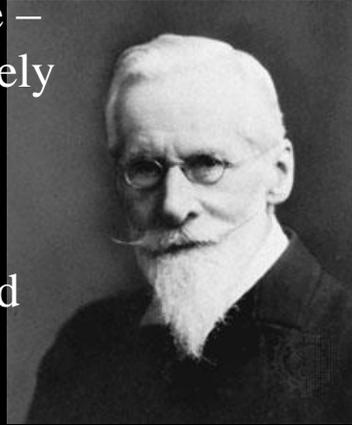
3.) $m_e = 9.1 \times 10^{-31}\ kg$

4.) $spin = 1/2$

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Early Observations - Electricity *Demo!*

- Positive and negative charges
- Like charges repel, opposites attract

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# Sir William Crookes 1870's

Cathode – Negatively charged

Anode – Positively charged

http://www.britannica.com/biography/William-Crookes

http://www.crtsite.com/page7.html

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# Sir William Crookes 1870's

- "Cathode rays" travel in straight lines

- Obstructions produce "shadows"
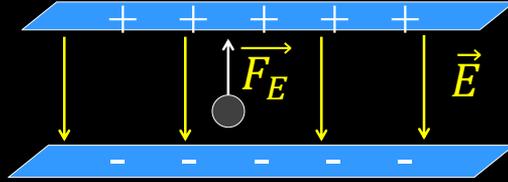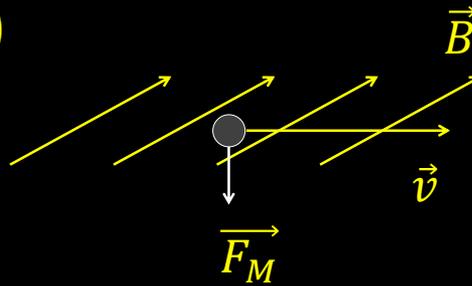
- Deflected by external magnetic and electric fields

http://www.britannica.com/biography/William-Crookes
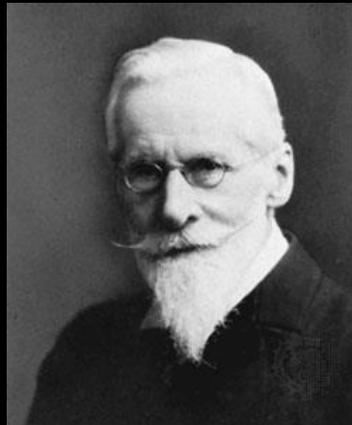
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4

Since $q < 0$, Force is antiparallel to E-field

$$\overrightarrow{F_E} = q\vec{E}$$

$\overrightarrow{F_E}$ $\vec{E}$

Force is perpendicular to B-field and velocity!

$$\overrightarrow{F_M} = q(\vec{v} \times \vec{B})$$
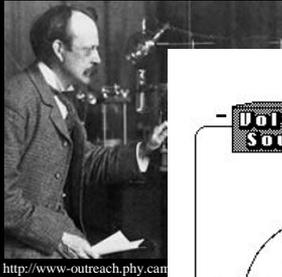
$\vec{B}$

$\vec{v}$

(Right-hand rule)

$\overrightarrow{F_M}$

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# Sir J.J. Thomson 1890's

http://www-outreach.phy.cam

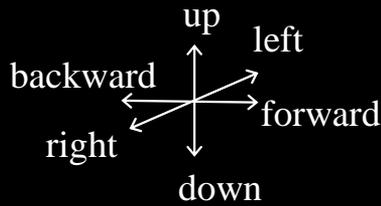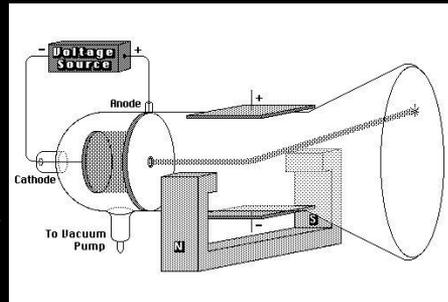Voltage Source

Anode

Cathode

To Vacuum Pump
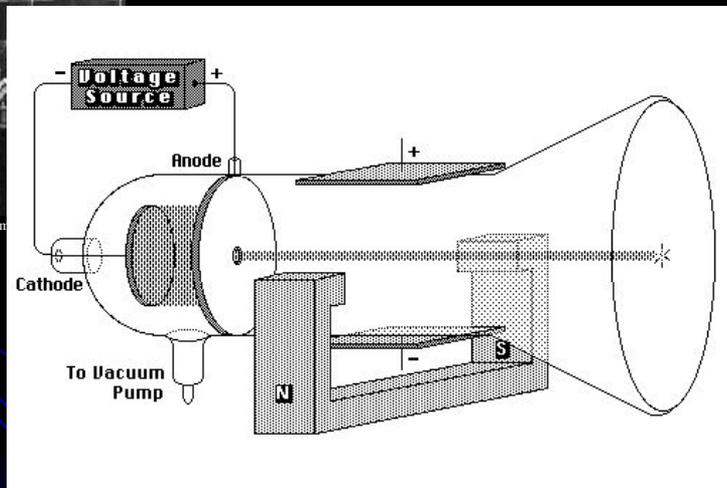
http://www.hcc.mnscu.edu/chem/abomb/page_id_15138.html

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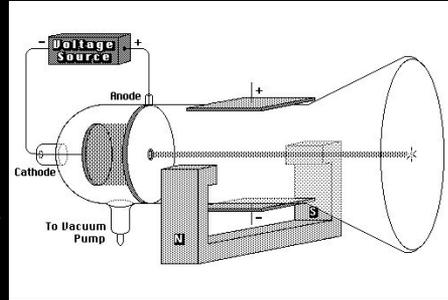
5

TOP HAT

up
left
backward
forward
right
down

Force due to electric
field pushes electrons…
a.) down        d.) left
b.) up          e.) forward
c.) right       f.) backward

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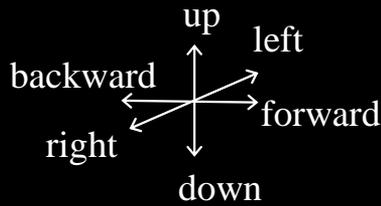


up
left
backward
forward
right
down

Force due to electric
field pushes electrons…
a.) down        d.) left
b.) up          e.) forward
c.) right       f.) backward

Discovering the Subatomic World                                    12

TOP HAT

up
left
backward
forward
right
down
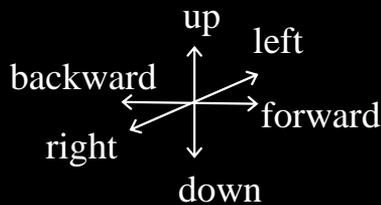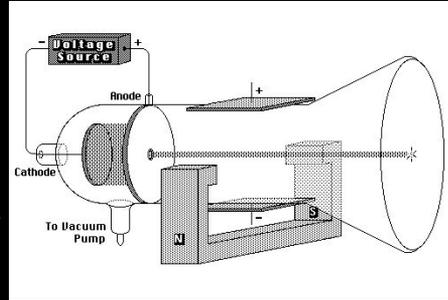
Force due to magnetic
field pushes electrons…
a.) down          d.) left
b.) up            e.) forward
c.) right         f.) backward
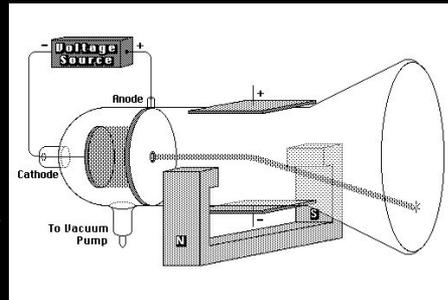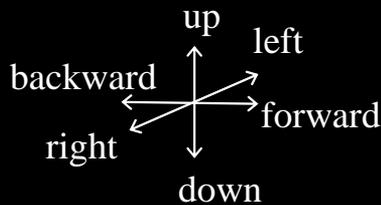
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up
left
backward
forward
right
down

Force due to electric
field pushes electrons…
a.) down          d.) left
b.) up            e.) forward
c.) right         f.) backward

Discovering the Subatomic World                    14

## Slide 15

**With no magnet…**
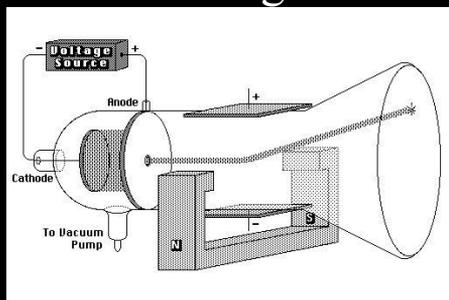
$$\overrightarrow{F_E} = m\vec{a}$$
$$qE = ma$$
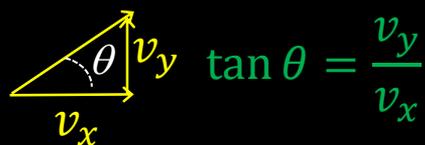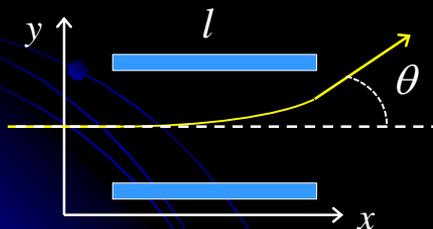
$$\tan\theta = \frac{v_y}{v_x}$$

$$v_y = v_x \tan\theta$$

$$v_y = at$$

$$v_x \tan\theta = a\left(\frac{l}{v_x}\right)$$

$$a = \frac{v_x{}^2}{l}\tan\theta$$

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## Slide 16

$$qE = m\frac{v_x{}^2}{l}\tan\theta \qquad \frac{q}{m} = \frac{v_x{}^2}{El}\tan\theta$$

**With the magnetic AND electric fields…**

$$\overrightarrow{F_E} = -\overrightarrow{F_B}$$
$$|q|E = |q||\vec{v}\times\vec{B}|$$
$$E = v_x B$$
$$v_x = \frac{E}{B}$$

$$\frac{q}{m} = \frac{E}{B^2 l}\tan\theta$$
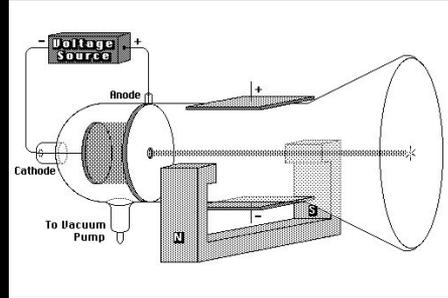
Discovering the Subatomic World  16

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

Thomson could determine the charge to mass ratio of the electron!
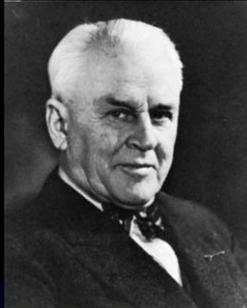


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A modern example

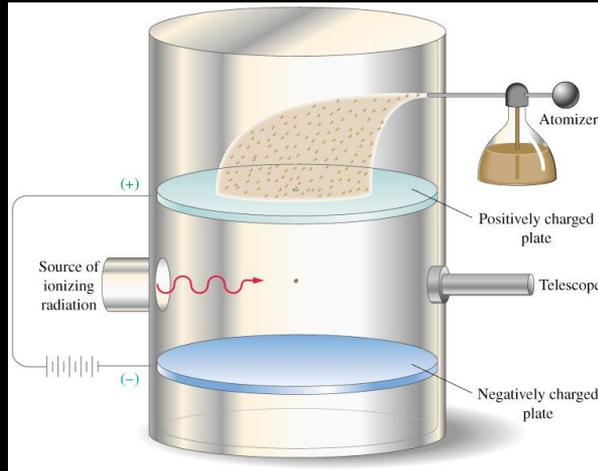*Demo!*

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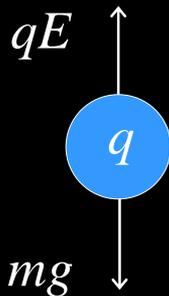# Robert Millikin determines the charge of the electron (1911)

http://www.britannica.com/biogra
phy/Robert-Andrews-Millikan

## Millikin Oil Drop Experiment

Atomizer

(+)

Positively charged
plate

Source of
ionizing
radiation

Telescope

(−)

Negatively charged
plate

http://www.timerime.com/en/event/419831/Robert+Millikan/

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$qE$

$q$

$mg$
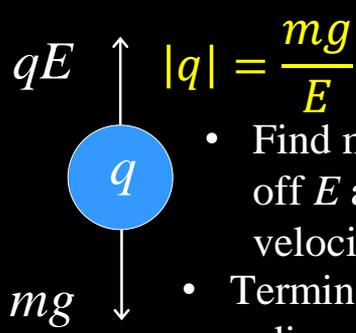
Adjust the electric force until it balances the weight of the drop

$$|q|E = mg$$

$$|q| = \frac{mg}{E}$$

Sounds simple.

Discovering the Subatomic World
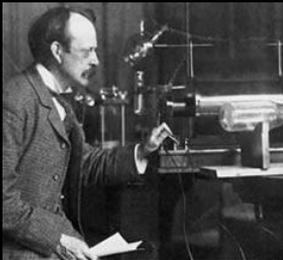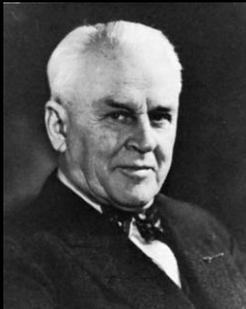
20

$$qE \uparrow \qquad |q| = \frac{mg}{E}$$

$q$

$mg \downarrow$

- Find mass of drop by turning off $E$ and measuring terminal velocity
- Terminal velocity is related to radius of drop. $m = \rho V$

- Charge on drop can change during experiment

- $q = Ne$

- Thousands and thousands of drops needed to find smallest quantized difference in charge on drop

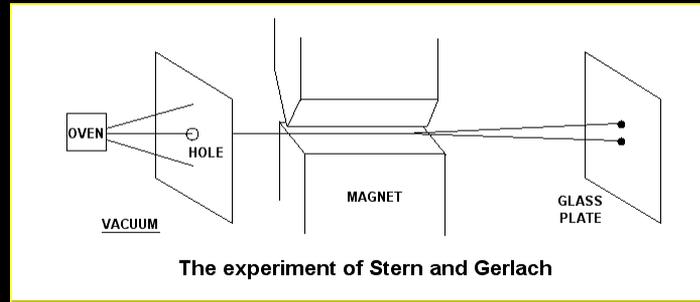Discovering the Subatomic World

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$$q = -1.6 \times 10^{-19} \ C$$

$$m_e = 9.1 \times 10^{-31} \ kg$$

$$m_e c^2 = 0.511 \times 10^6 \ eV$$

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## Stern-Gerlach Experiment (1921)

Oven produces a beam of Ag Atoms



The experiment of Stern and Gerlach

http://www.physics.rutgers.edu/~zrwan/physics/

Collimated and sent thru *B*-field then to collector

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Silver – 46 electrons in inner shells and a single electron in *5s* shell.

The single outer electron determines how Ag responds to inhomogeneous magnetic field.

For *5s* electron, $\ell = 0$ and $m_\ell = 0$

In a homogeneous magnetic field, the forces are equal and opposite (but there's a torque)

http://labman.phys.utk.edu/phys222core/modules/m4/magnetic%20materials.htm
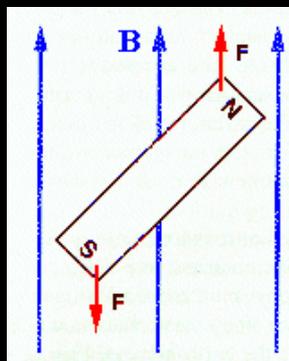
If the external field is stronger at the top (inhomogeneous), the force upwards will be greater than the force downwards

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In general…        $\vec{F} = -\vec{\nabla} V$

For an inhomogeneous B-field…

$$\vec{F} = -\vec{\nabla}\left(- \vec{\mu} \cdot \vec{B}\right)$$

$$\frac{\partial B_z}{\partial z} \neq 0$$

$$F_z = \mu_z \frac{dB_z}{dz}$$   $$F_z = -m_\ell \mu_B \frac{dB_z}{dz}$$

We expect atoms experience a force along z that depends on magnetic quantum number

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The Stern-Gerlach experiment. On the photographic plate are two clear tracks.

http://quantum.goetheanum.org/Stern-Gerlach-experiment-in-discussion.7888.0.html

For $\ell = 0\ m_\ell = 0$ and there should be no force.

Instead we get atoms separated into two trajectories

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Explanation requires a new type of angular momentum!
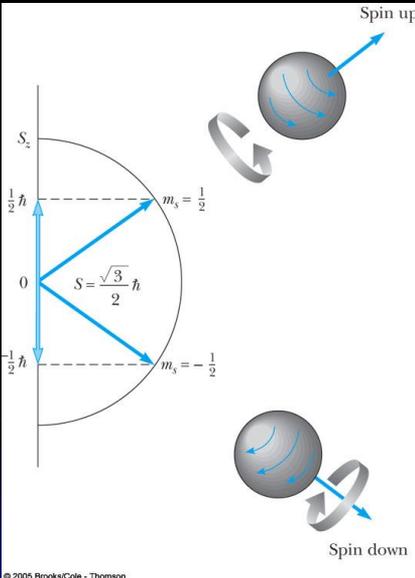
Spin $\quad S = \sqrt{s(s+1)}\hbar \qquad S_z = m_s \hbar$

$$m_s = -s, -(s-1)...(s-1), s$$

For $e^-$'s (and protons and neutrons and…)

$$s = \tfrac{1}{2} \qquad m_s = -\tfrac{1}{2}, +\tfrac{1}{2}$$

$$S = \sqrt{\tfrac{3}{4}}\hbar \qquad S_z = \pm \frac{\hbar}{2}$$

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Bad picture – $e^-$ spin is not about spinning balls of charge

Weird form of A.M.

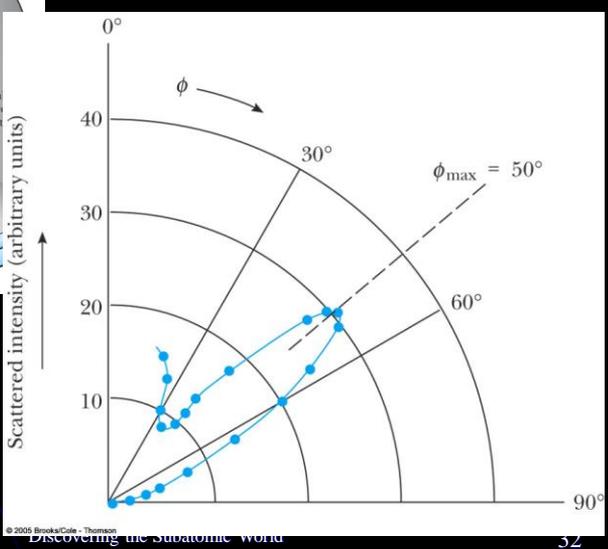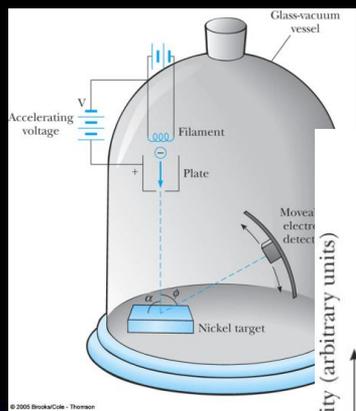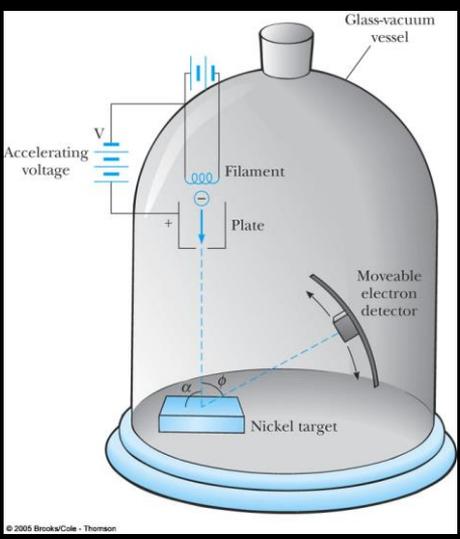Spin is an intrinsic property of a particle (Like mass, charge, etc.)

Things we know about the electron

1.) It's "elementary"

2.) $q = -1.6 \times 10^{-19}$ C

3.) $m = 9.1 \times 10^{-31}$ kg

4.) spin = 1/2

Davisson-
Germer Expt
*(1927)*

*54 eV* e⁻'s on Ni
crystal sample



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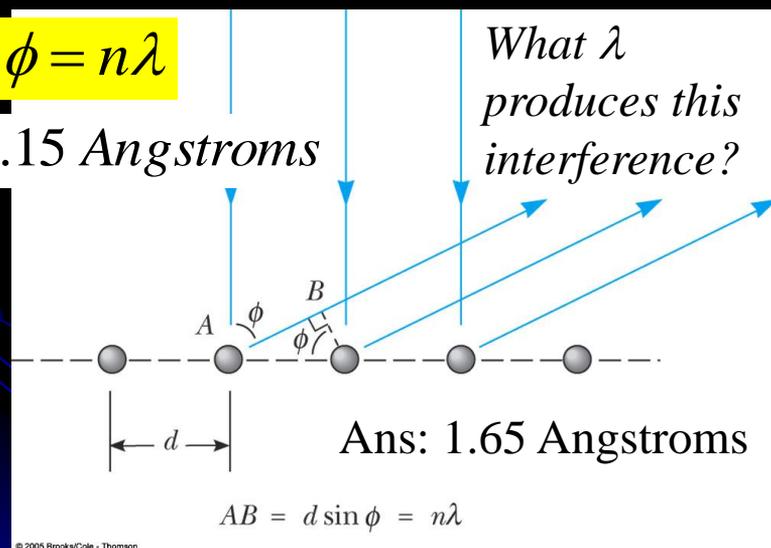
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## Davisson-Germer Expt - Explanation
### (for low energy e⁻'s – single layer of atoms)

$$d \sin \phi = n\lambda$$

$$d = 2.15 \, Angstroms$$

*What $\lambda$ produces this interference?*

Ans: 1.65 Angstroms

$$AB = d \sin \phi = n\lambda$$

© 2005 Brooks/Cole - Thomson

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## Prince Louis de Broglie (1923)

$$\lambda = \frac{h}{p}$$

De Broglie Wavelength of a "particle"

Momentum of the "particle"

### Light and matter both exhibit *duality*

TOP HAT

$$\lambda = \frac{hc}{\sqrt{2mc^2K}}$$

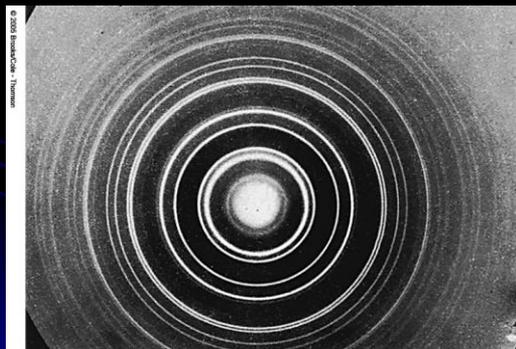What's the de Broglie wavelength (in nm) for e⁻'s accelerated through 54 V? (non-relativistic)

$$hc = 1240 \; eV \cdot nm$$
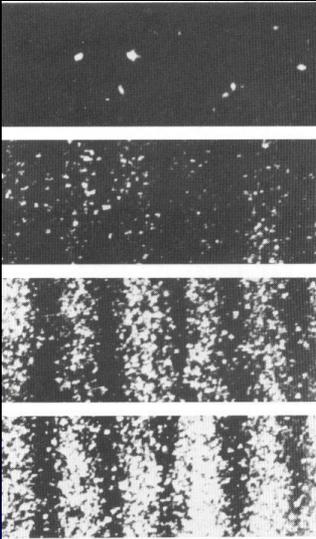
$$mc^2 = 0.511 \times 10^6 \; eV$$

Davisson-Germer Expt –

Demo!

Provided first evidence for interference of de Broglie waves for $e^-$'s!



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Wave-particle duality for electrons!

Electrons - 2 slits

Likewise: interference observed for e, n, atoms!

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TOP HAT

$$\lambda = \frac{hc}{pc}$$

What's the de Broglie wavelength (in nm) for e⁻'s accelerated through 540,000 V? (relativistic)

$$hc = 1240 \, eV \cdot nm$$

$$mc^2 = 0.511 \times 10^6 \, eV$$

$$E^2 = (pc)^2 + (mc^2)^2$$

$$E = K + mc^2$$