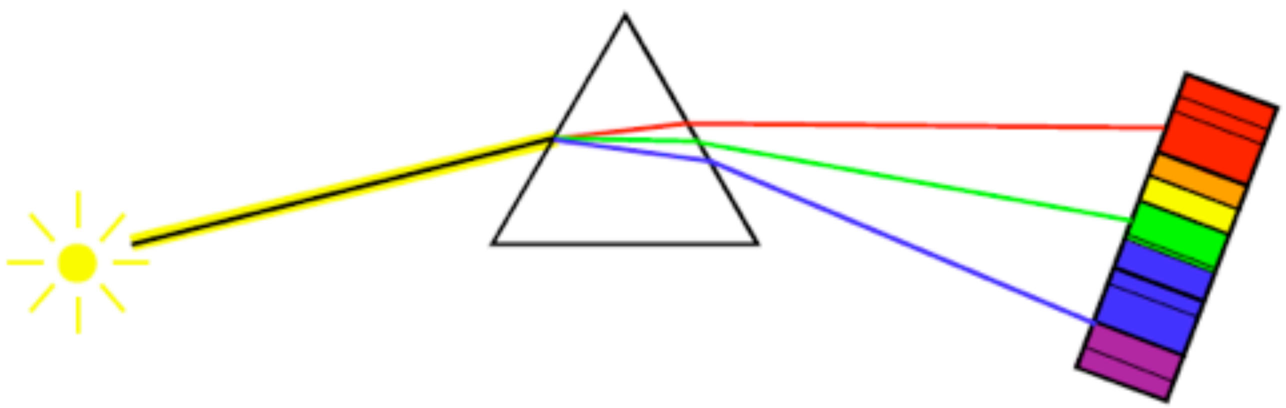
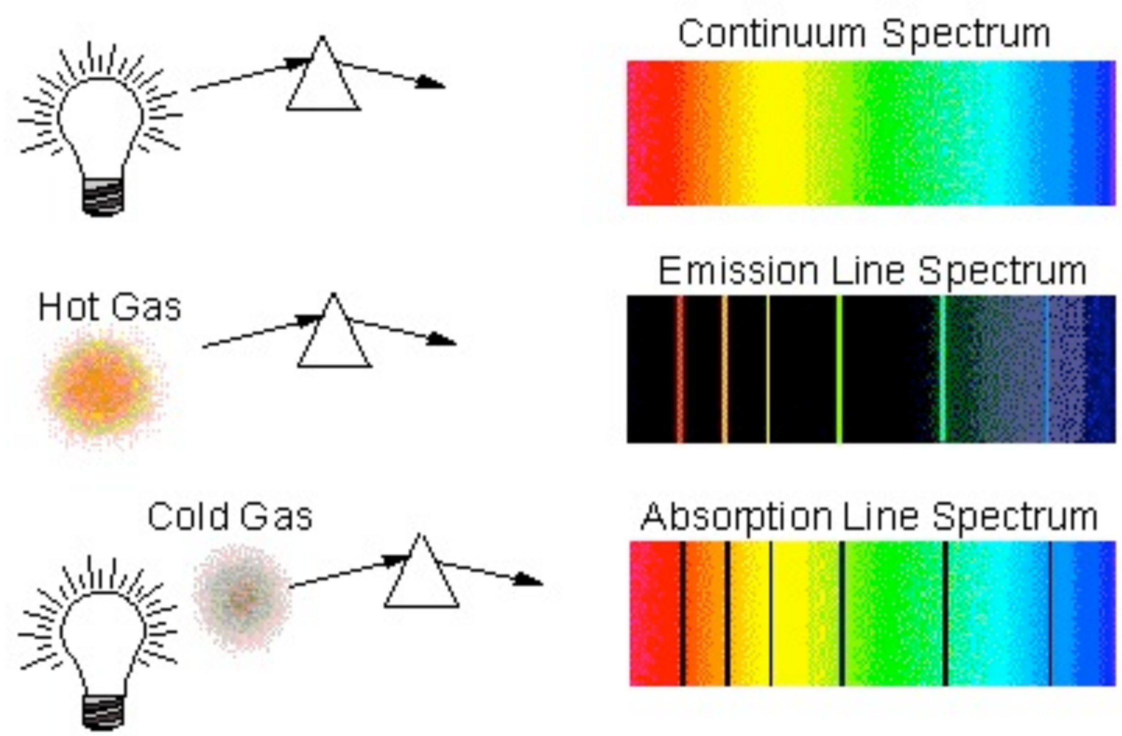
# Outline

- Spectral Lines
    - Lyman, Balmer, Paschen Series
- Models of Atoms
    - Rutherford Scattering
- Classical Hydrogen Atom
- Bohr Atom
    - Limitations

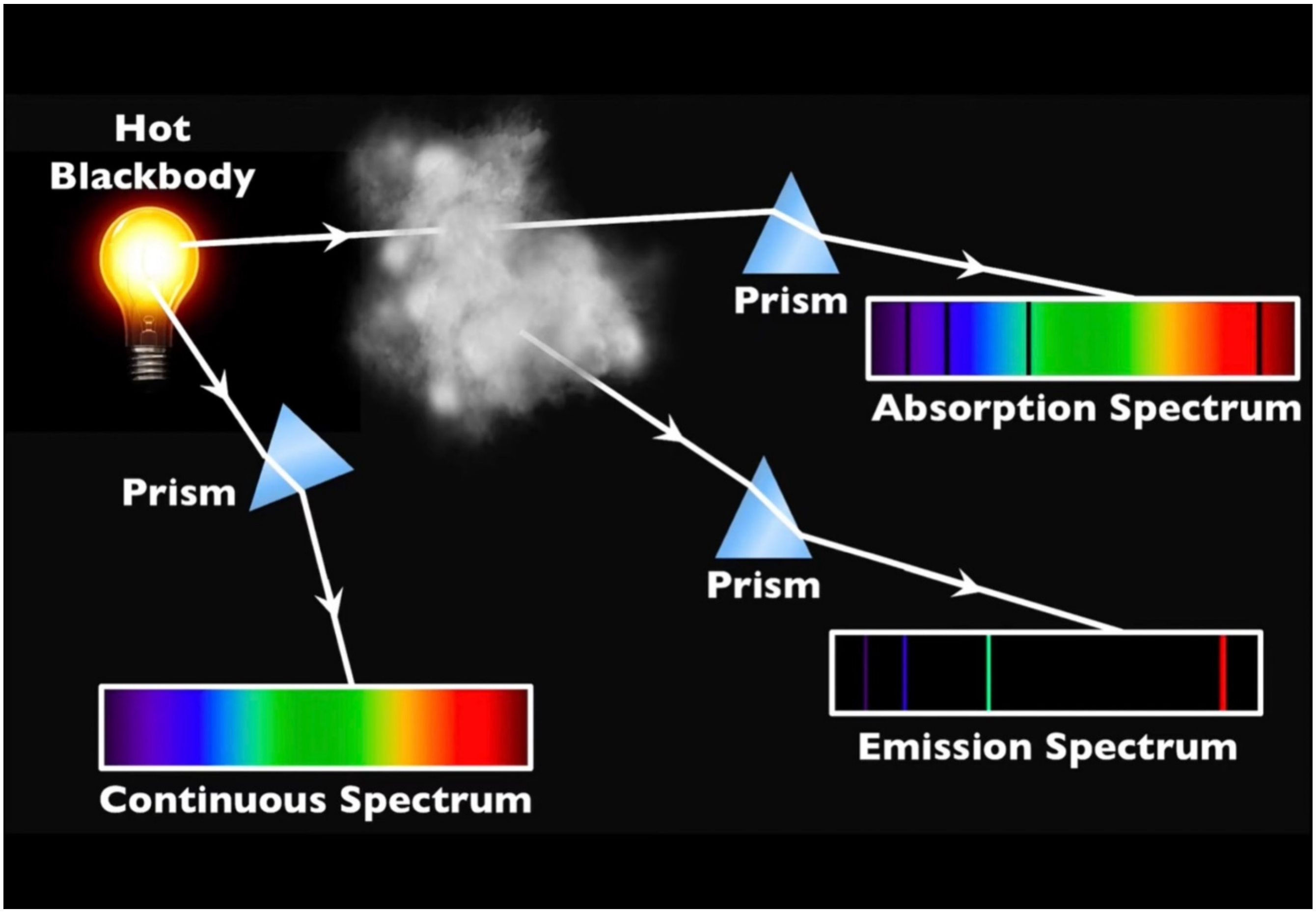
# Spectral Lines

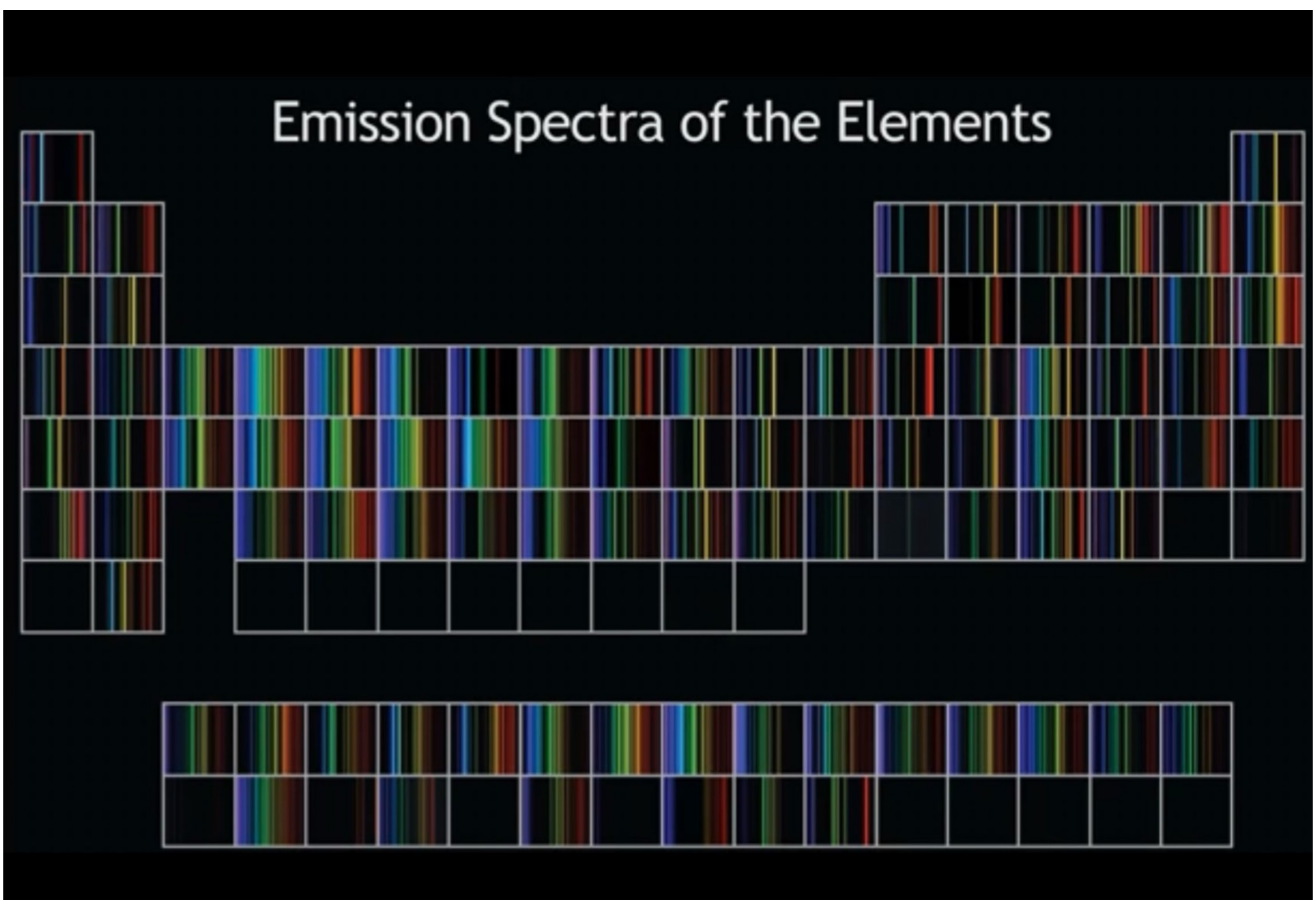





- 1814-1824: Von Fraunhofer discovered absorption lines in sun.
- 1850's: Kirchhoff discovered characteristic emission lines of elements
- 1859: Kirchoff and Bunsen discovered new elements, Cesium and Rubidium, by first observing their spectral lines.

Image: http://www.astro-assist.com


Hot
Blackbody
Prism
Absorption Spectrum
Prism
Prism
Emission Spectrum
Continuous Spectrum


Emission Spectra of the Elements

# Concept Test

- A bright star shines through a dark gaseous nebula. The spectrum of this star will consist primarily of
  - Bright Lines
  - Dark Lines ← Star = "light bulb"
  - Neither

# Balmer Series

- 1885: Balmer found a formula for the wavelengths of the spectral lines in Hydrogen:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{4} - \frac{1}{n^2}\right)$$

where $n=3,4,5,\ldots$

The constant $R_H$ is Rydberg's constant:

$$R_H = 1.096776 \times 10^7 \ m^{-1}$$

# Rydberg Equation

**Table 3.2 Hydrogen Series of Spectral Lines**

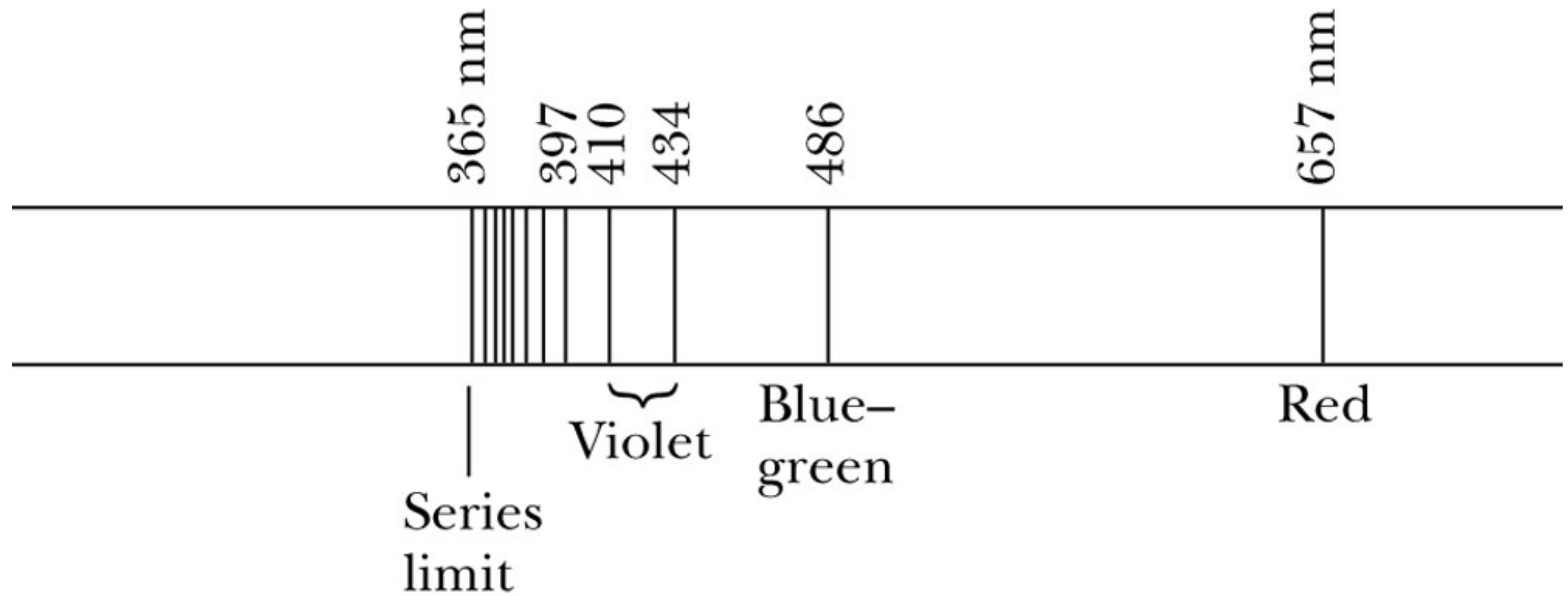
| Discoverer (year) | Wavelength | $n$ | $k$ |
|---|---|---|---|
| Lyman (1916) | Ultraviolet | 1 | >1 |
| Balmer (1885) | Visible, ultraviolet | 2 | >2 |
| Paschen (1908) | Infrared | 3 | >3 |
| Brackett (1922) | Infrared | 4 | >4 |
| Pfund (1924) | Infrared | 5 | >5 |



$$\frac{1}{\lambda} = R_H\left(\frac{1}{n^2} - \frac{1}{k^2}\right) \qquad R_H = 1.096776 \times 10^7\ \text{m}^{-1}$$

Image: Thornton and Rex

# Interpretation (Bohr)



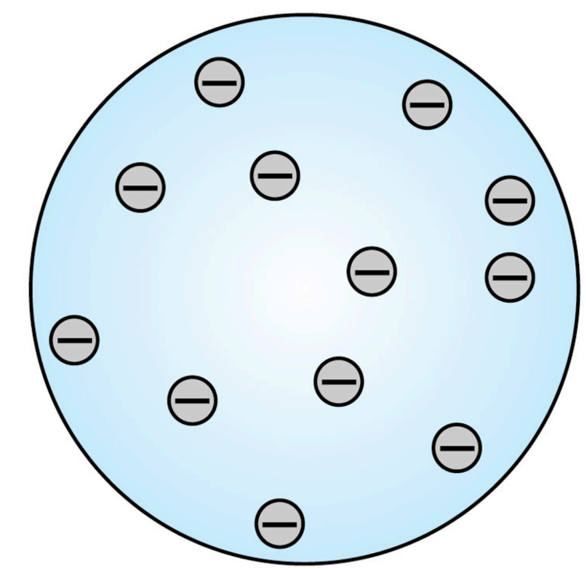


- Discrete spectral lines
  - E=hν (Planck)
  - Discrete Energies!
- Atom interacting with light
- Hence, discrete atomic "states"
- *Quantization*

Image: Thornton and Rex

# Models of Atoms

- Electrons + some positive charge must reside inside atom: but how?
- Pre-history: Thomson's Plum-Pudding
    - Electrons embedded in uniform + background ("pudding")

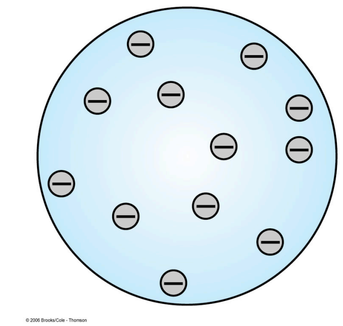




- Heat atoms, electrons vibrate, create E&M radiation (light)

Image: Thornton and Rex

# Concept Test



- α particles are the nucleii of Helium atoms, have a charge of +2 and a mass of approximately 8000 times $m_e$. If the α particlesscatter off of a "plum pudding" atom, a continuous distribution of positive charge with a few (light) electrons embedded in it, we expect:
  - All of the α particles to be absorbed
  - All of the α particles to bounce backward
  - None of the α particles to bounce backward ←

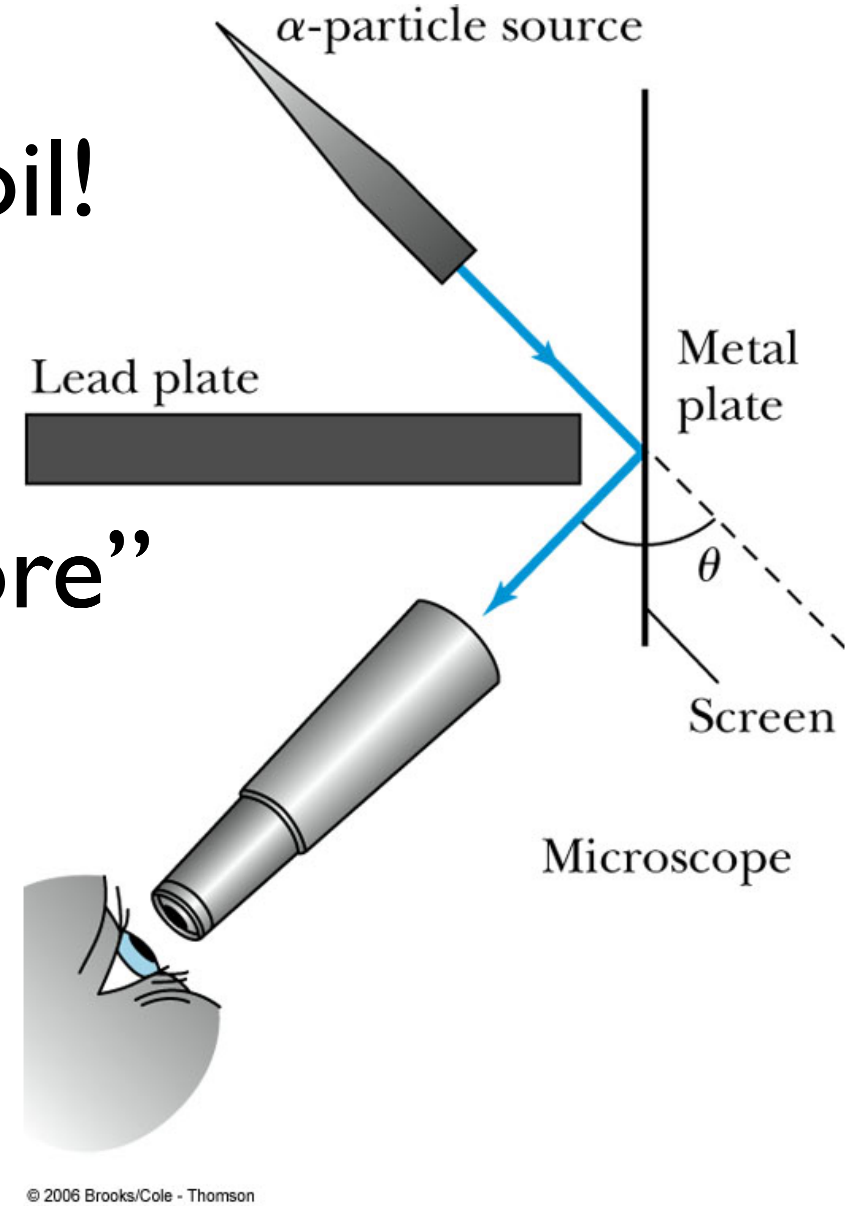
Image: Thornton and Rex

# Geiger and Marsden (1909)

- α rays (modern: He nucleii) "back-scatter" off of a thin gold foil!

- Rutherford (1911)
  - Atoms have a "hard charged core" of size ~$10^{-14}$m!

Ernest Rutherford
1871-1937
Nobel Prize 1908

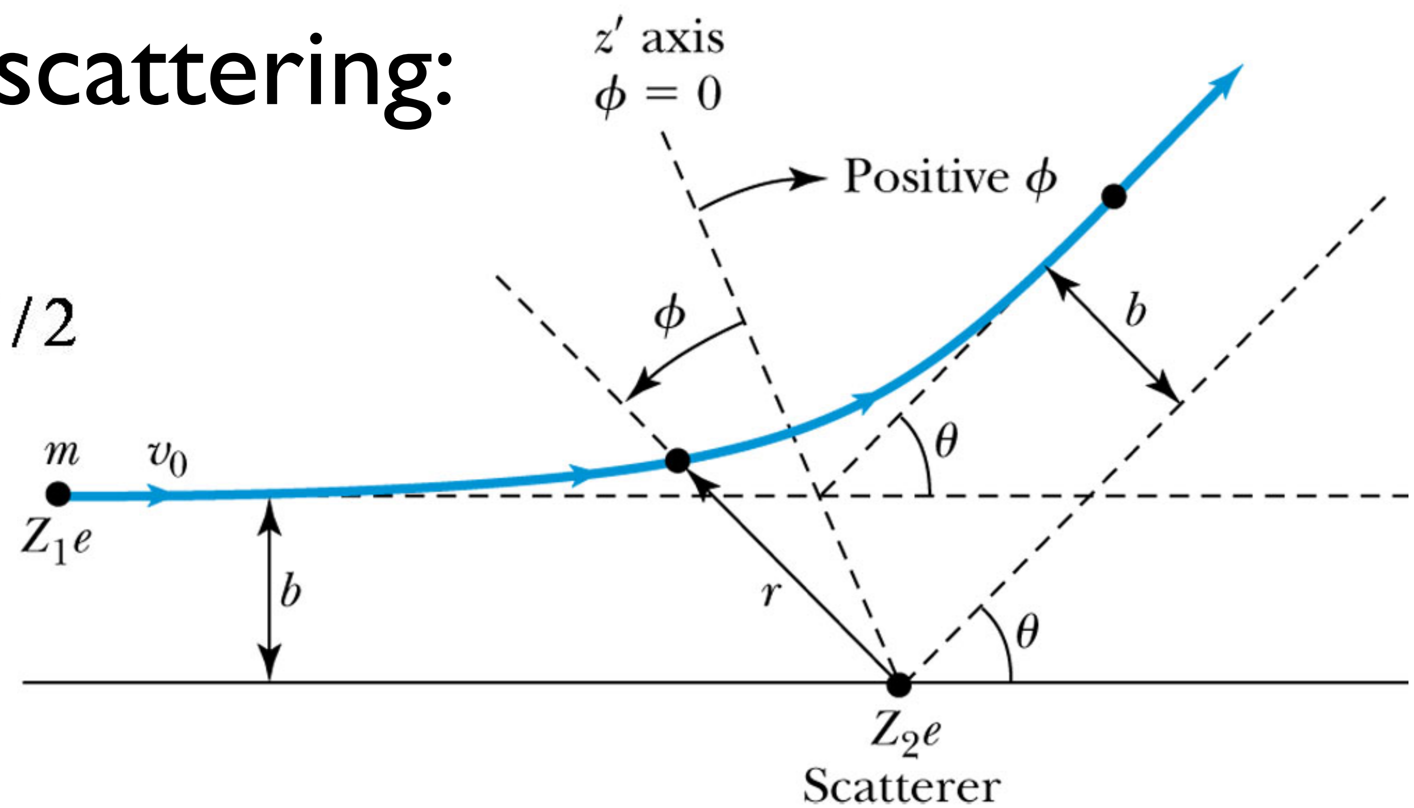



Images: Thornton and Rex
http://wikipedia.org

# Scattering Experiments

- We study the properties of atoms (and smaller objects) using *scattering experiments*.
- Two parameters: impact parameter (b) and scattering angle (θ)
- For Coulomb scattering:

$$b = \frac{Z_1 Z_2 e^2}{8\pi\varepsilon_0 K}\cot\frac{\theta}{2} \quad \text{where } K = m{v_0}^2/2$$

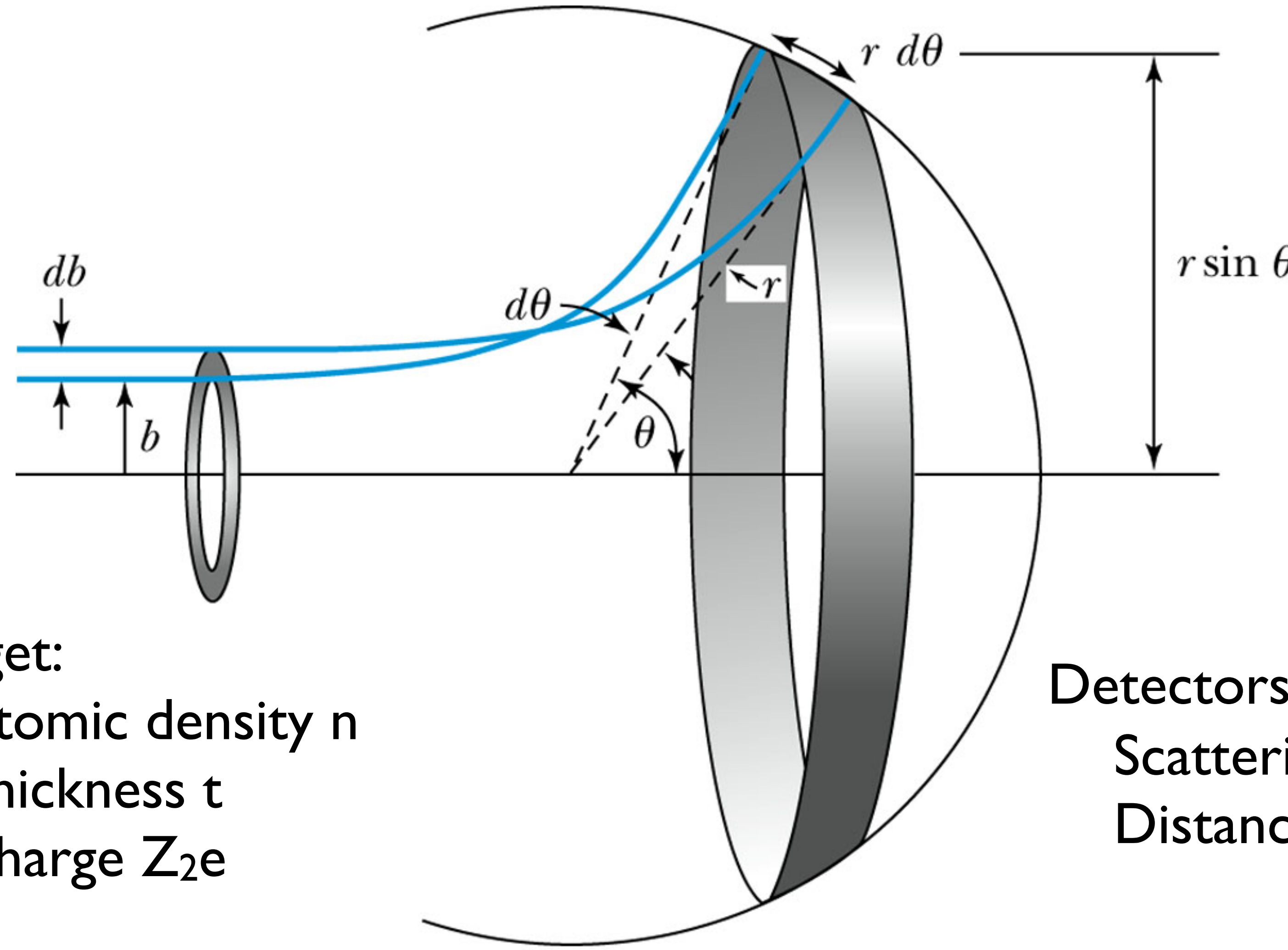





Images: Thornton and Rex

# Rutherford Scattering Formula

$N_i$ incoming particles
Charge $Z_1 e$
Kinetic Energy K




Target:
atomic density n
thickness t
charge $Z_2 e$

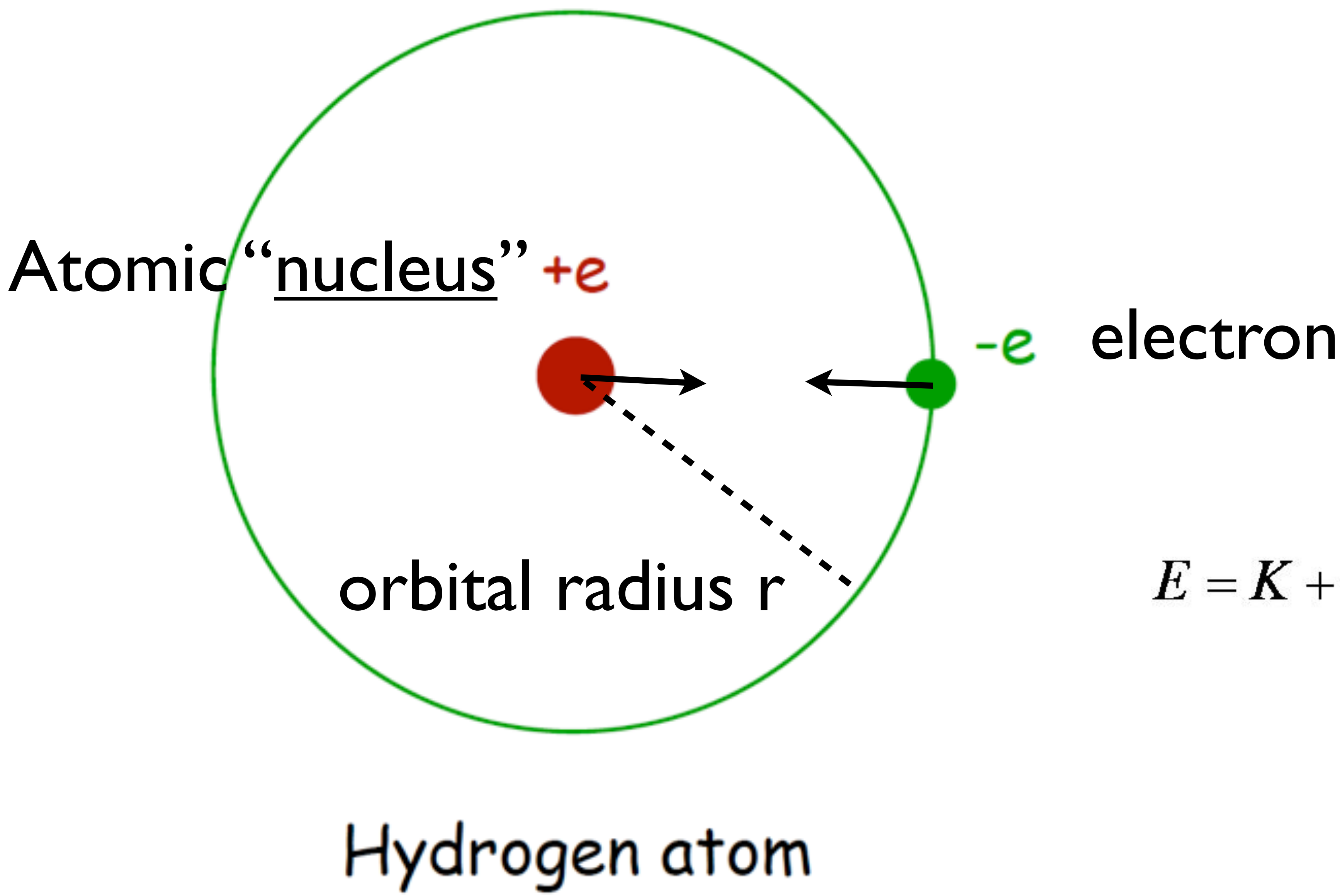
Detectors:
Scattering angle θ
Distance r



$$N(\theta) = \frac{N_i n t}{16}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{Z_1^{\,2} Z_2^{\,2}}{r^2 K^2 \sin^4(\theta/2)}$$

Images: Thornton and Rex

# Rutherford's Atomic Model




Bound by Coulomb Force

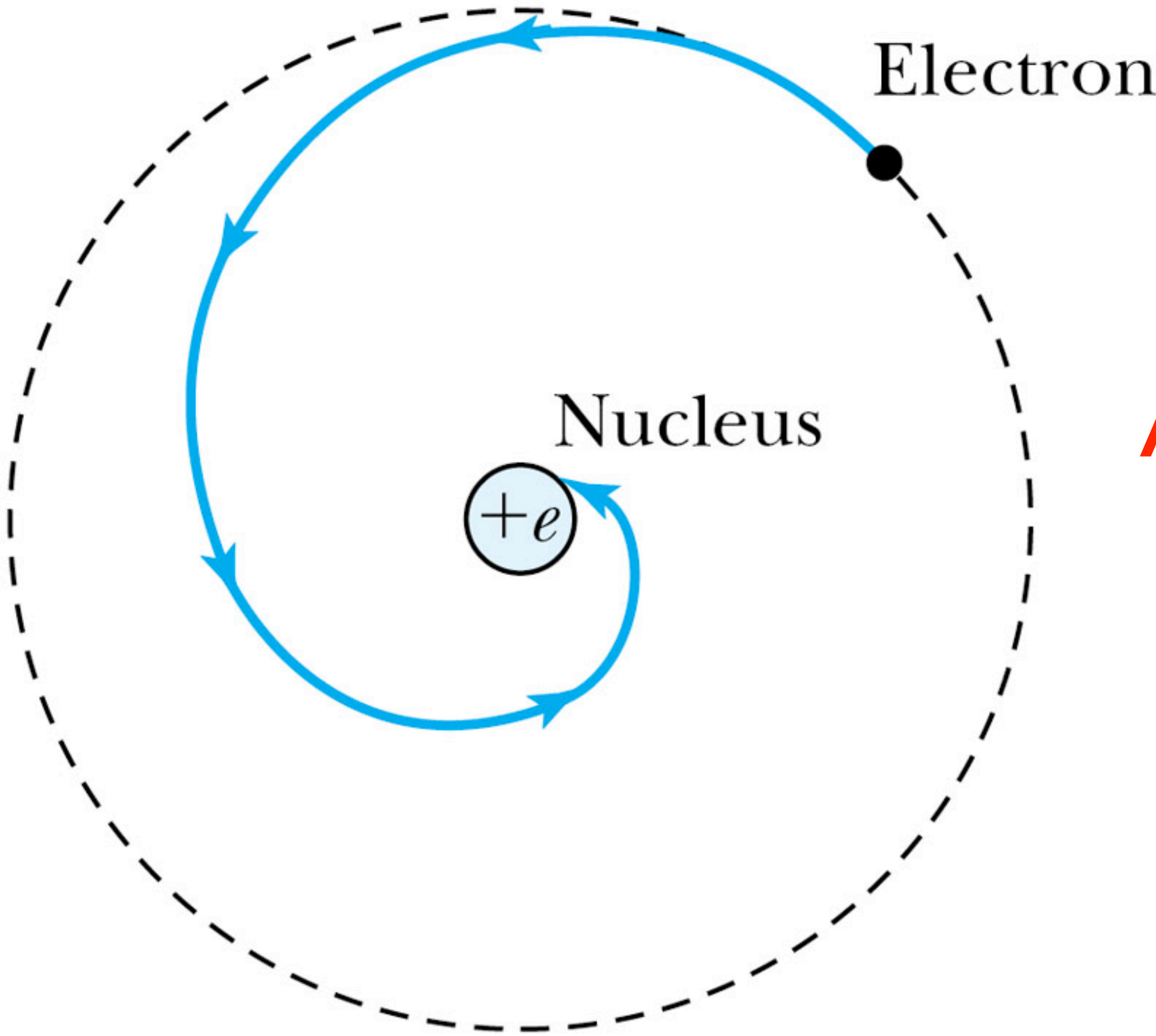
$$\vec{F}_e = \frac{-1}{4\pi\varepsilon_0}\frac{e^2}{r^2}\hat{e}_r = \frac{mv^2}{r}$$

$$E = K + V = \frac{e^2}{8\pi\varepsilon_0 r} - \frac{e^2}{4\pi\varepsilon_0 r} = \frac{-e^2}{8\pi\varepsilon_0 r}$$

nucleus: $10^{-14}$ m

Images: Thornton and Rex

# Problem with the Classical Model





Accelerating electrons should radiate energy - and crash into the nucleus!

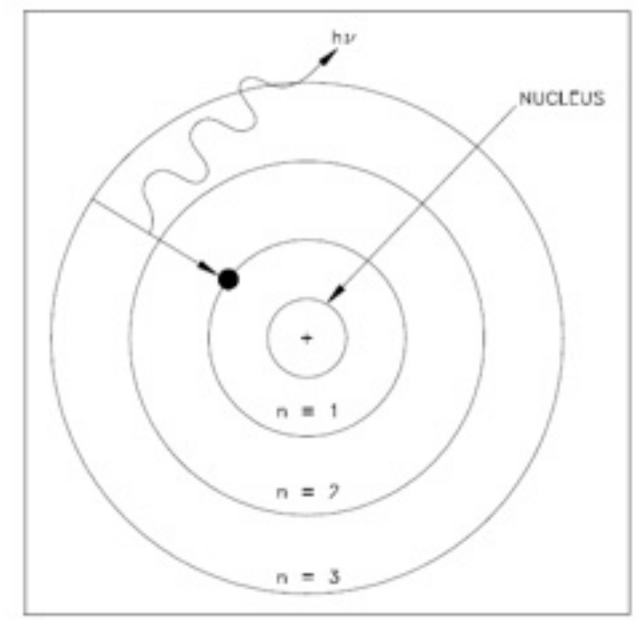
Images: Thornton and Rex

# Bohr Model

- Electrons can exist only in particular (quantized) “stationary states”.
- Spectral lines correspond to energy *differences* between stationary states, when electrons “jump” between states.
- Angular momentum of electron quantized, equal to an integer multiple of $h/2\pi$!

$\hbar = h/(2\pi)$

$\hbar = 1.05 \times 10^{-34}$ J•s

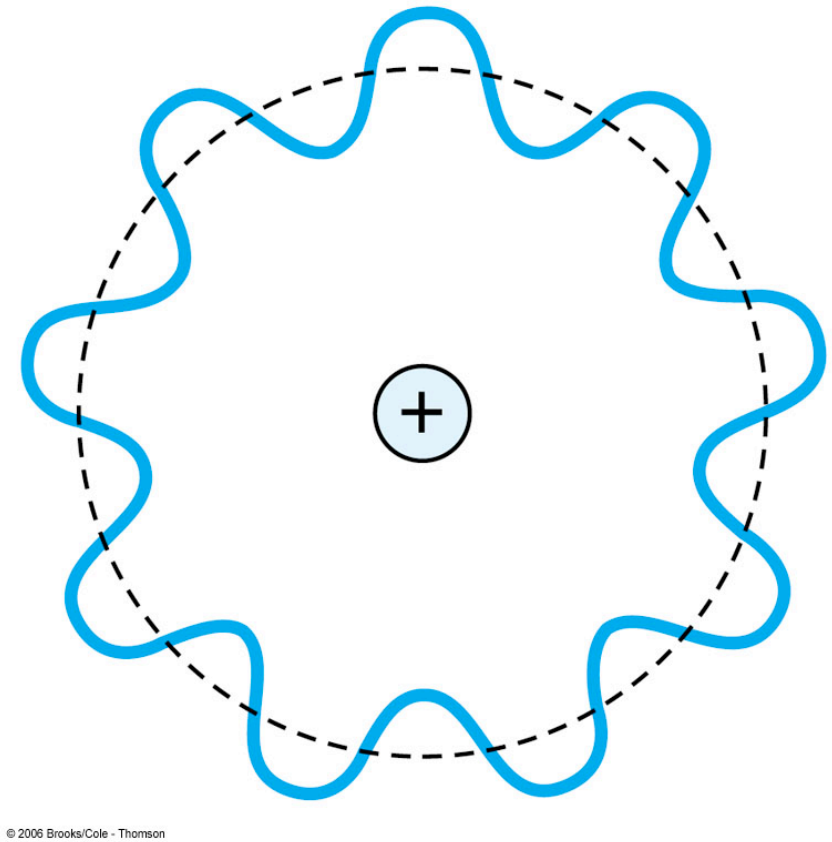



Niels Bohr
1885-1962
Nobel Prize 1922

Images: knowledgepublications.com

# de Broglie & Bohr

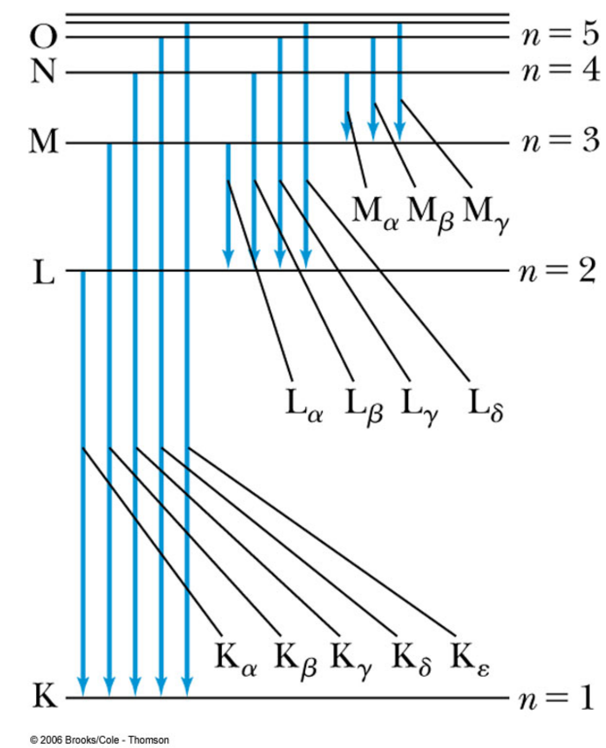
- Bohr: $L = mvr = nh/2\pi$
- de Broglie: $\lambda = h/p$
- $p = mv$, $pr = nh/2\pi$
- Ergo: $n\lambda = 2\pi r$




- "Stationary State"=orbit with an integral number of electron de Broglie wavelengths!
- "Stationary States" = standing electron waves!

Image: Thornton and Rex

# Bohr Limitations




- Nucleus is not infinitely heavy
  - $m_e \to \mu$=reduced mass
- Many electron atoms?
  - Not all electrons in n=1 state! Why?
- No systematic way forward
  - What about other systems?
  - How do quantum systems evolve?

Image: Thornton and Rex

# Summary, so far

- Bohr’s model of the atom
  - Builds on Rutherford’s “planetary” model.
  - “Stationery” states = “standing electron waves”.
  - Spectral lines = photon emission via electron “jumps” to different levels.

# Outline

- Bohr Model Numbers
  - Bohr Shell Hypothesis
  - X-ray Spectra and Atomic Number
- Waves vs. Particles
  - Fourier Series/Transforms
  - Complex Exponentials
- Born's Interpretation of $\Psi$

# Bohr Model

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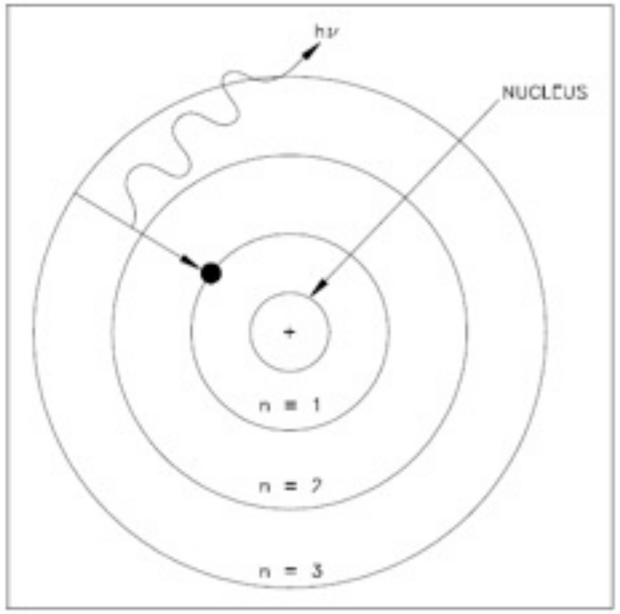



Niels Bohr
1885-1962
Nobel Prize 1922

Images: knowledgepublications.com
wikipedia.org

# Bohr Radius (H atom)

Coulomb Force $\frac{e^2}{4\pi\epsilon_0 r_n^2} = \frac{m_e v^2}{r_n} = \frac{L^2}{m_e r_n^3}$ Centripetal Force

Bohr Quantization $L = n\hbar$

$$r_n = \frac{4\pi\epsilon_0 n^2 \hbar^2}{m_e e^2} = a_0 n^2$$

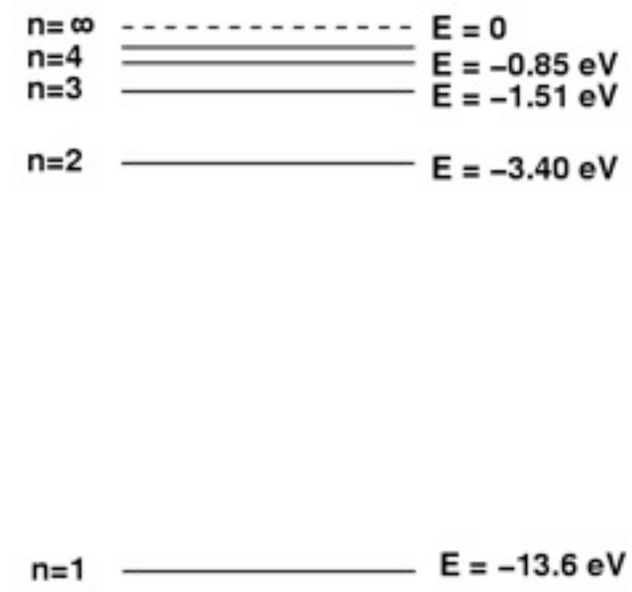
nucleus: $10^{-14}$ m (Rutherford)

Bohr Radius $a_0 = \frac{4\pi\epsilon_0 \hbar^2}{m_e e^2} = 0.53 \times 10^{-10}\,\mathrm{m} = 0.53\mathring{A}$

$$\frac{v}{c} = \frac{e^2}{4\pi\epsilon_0 c} \cdot \frac{1}{n} \equiv \frac{\alpha}{n} \qquad \alpha = \frac{e^2}{4\pi\epsilon_0 c} \approx \frac{1}{137}$$

# Bohr H Energy Levels

$$E_n = -\frac{e^2}{8\pi\varepsilon_0 r_n} = -\frac{e^2}{8\pi\varepsilon_0 a_0 n^2} \equiv -\frac{E_0}{n^2}$$




$E_0 \approx 13.6$ eV

Transition from state n to state m:

$$\begin{aligned} E_{k\to n} &= E_k - E_n \\ &= \frac{hc}{\lambda} \\ &= E_0\left(\frac{1}{n^2} - \frac{1}{k^2}\right) \end{aligned}$$

$$\begin{aligned} \frac{1}{\lambda} &= \frac{E_0}{hc}\left(\frac{1}{n^2} - \frac{1}{k^2}\right) \\ &= R_\infty\left(\frac{1}{n^2} - \frac{1}{k^2}\right) \\ R_\infty &= \frac{13.6\,\text{eV} \cdot 1.602 \times 10^{-19}\,\text{J/eV}}{1.986 \times 10^{-25}\,\text{J m}} \\ &= 1.097 \times 10^7\,\text{m} \end{aligned}$$

Bohr model reproduces Rydberg formula!

Image: www.physicsforums.com

# Concept Test

- Let's apply the Bohr model to carbon, whose nucleus has Z=+6. The number of electrons in the neutral atom is therefore
  - 4
  - 5
  - 6 ← Are all six electrons in the lowest energy stationary state?
  - 7

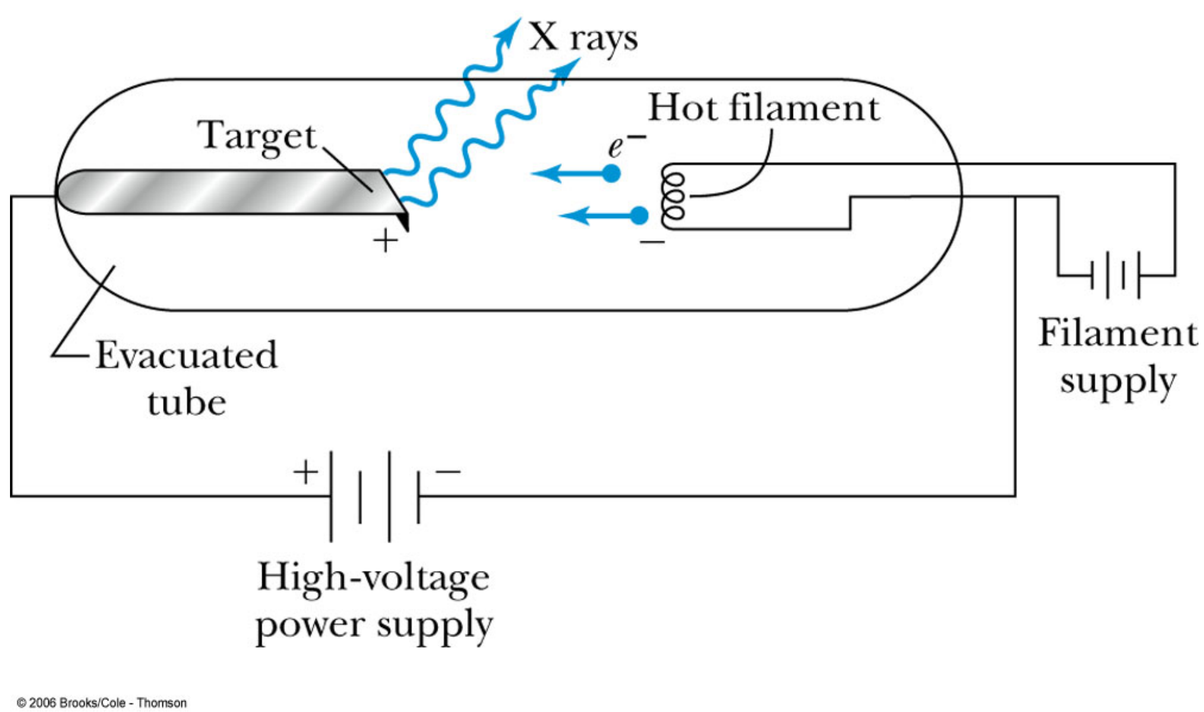
# Bohr Shell Hypothesis

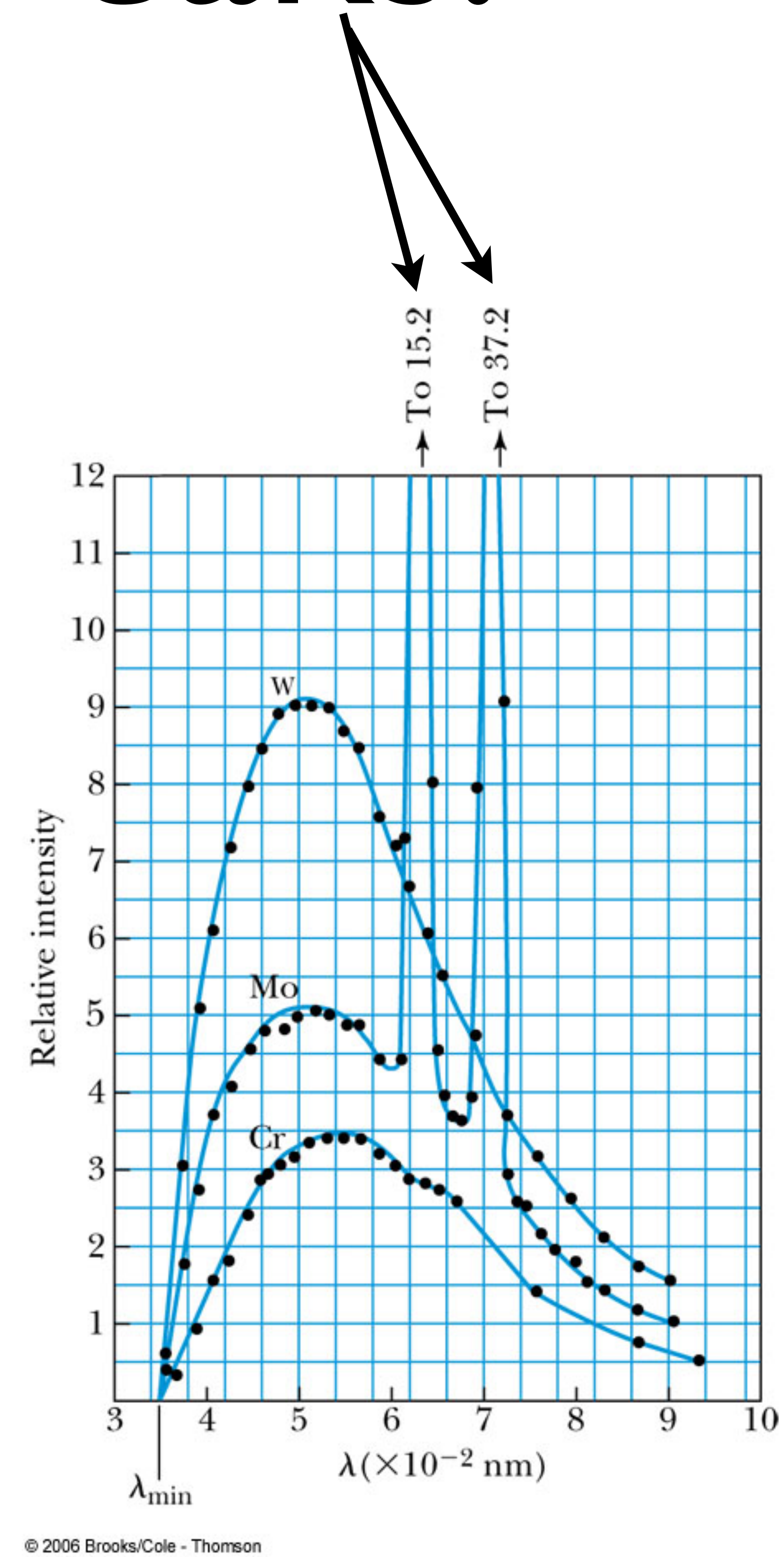
$$\frac{1}{\lambda_{k\rightarrow n}} = Z^2 R\left(\frac{1}{n^2} - \frac{1}{k^2}\right)$$

- Bohr model generalizes to any single-electron atom: $e^2 \rightarrow Ze^2$
- Bohr model yields many quantized energy levels for any atom, depending on n.
- Bohr asserted that any given shell could only hold a certain number of electrons - after it was filled, electrons must occupy the next available level. Why? (We will see!)

# X-Ray Spectra Peaks:

Inverse photoelectric effect:



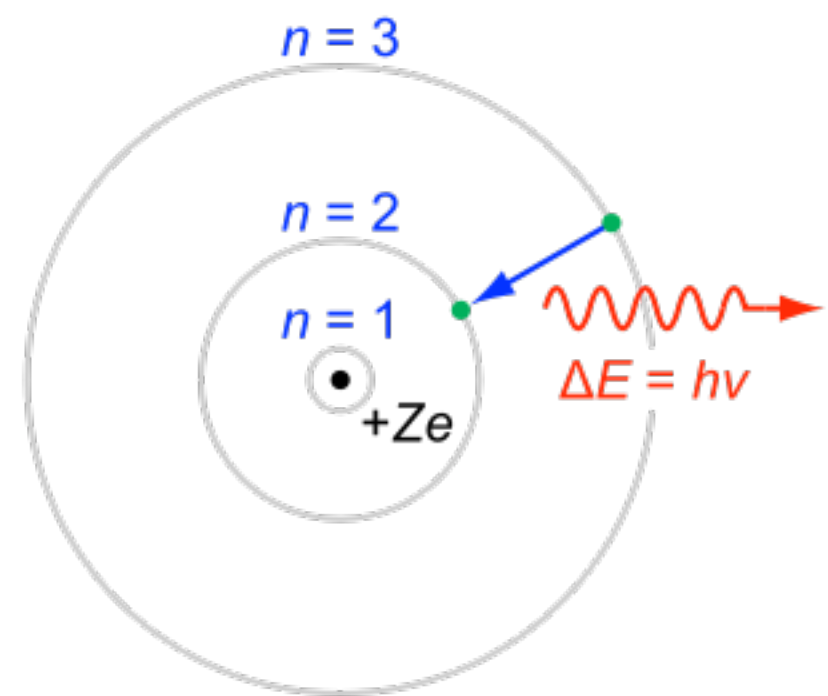




Can be explained in terms of shell hypothesis...

Images: Thornton and Rex

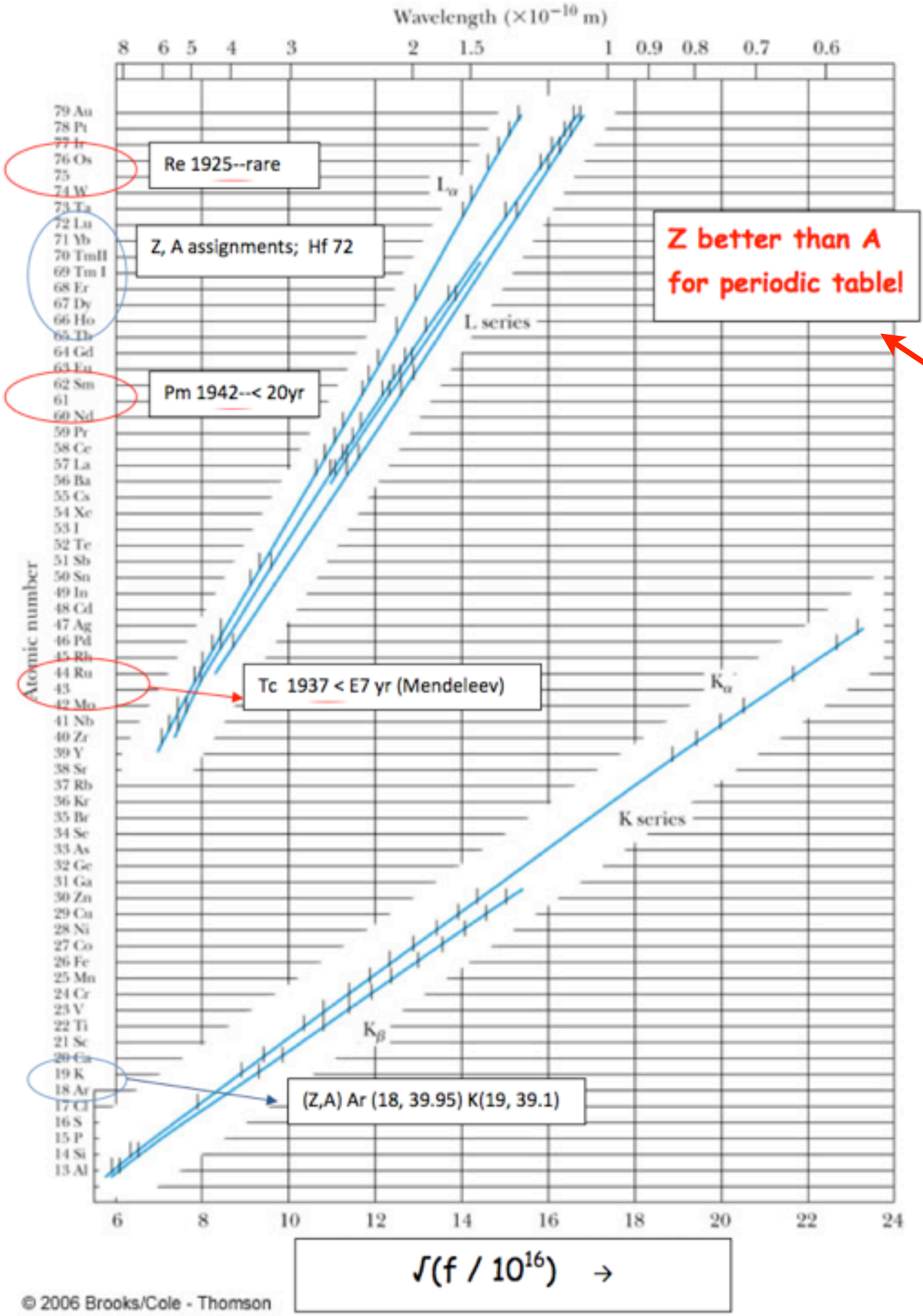
# X-ray Peaks II

- X-rays excite electrons from n=1 “shell” (K-shell).
- An electron from an upper shell cascades down to take its place
- Since $E_n \propto Z^2$, we expect square root of peak frequencies to be linear in Z!




Images http://wikipedia.org

# Moseley Plot (1913)

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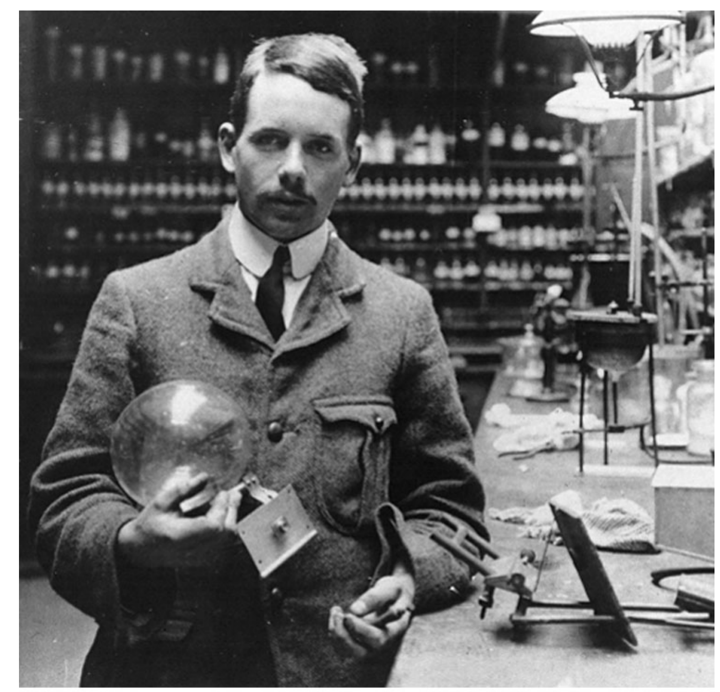
Corrected Mendeleev!




Henry Moseley
1887-1915

Images: Thornton and Rex