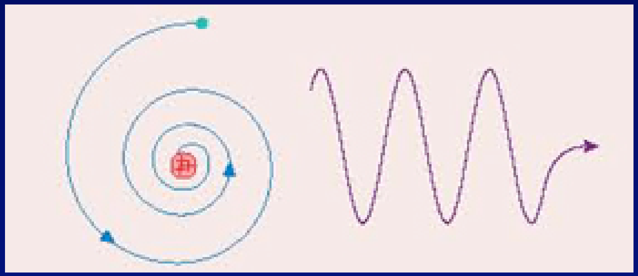
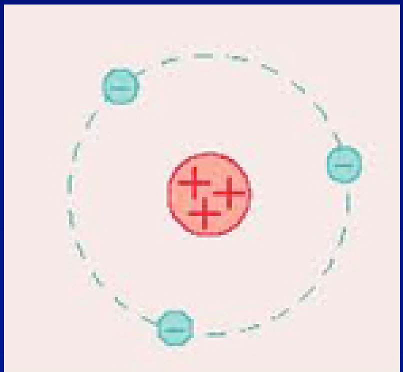
Chapter 38

Photons, Electrons and Atoms

- Blackbody radiation
- The photoelectric effect
- Compton effect
- Line spectra
- Nuclear physics/Bohr model
- Lasers
- Quantum mechanics





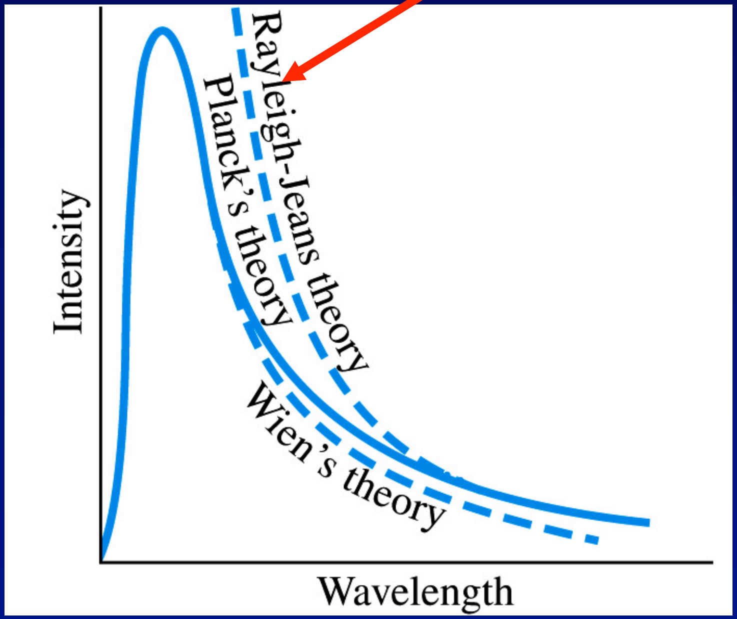
Blackbody radiation

New Topic

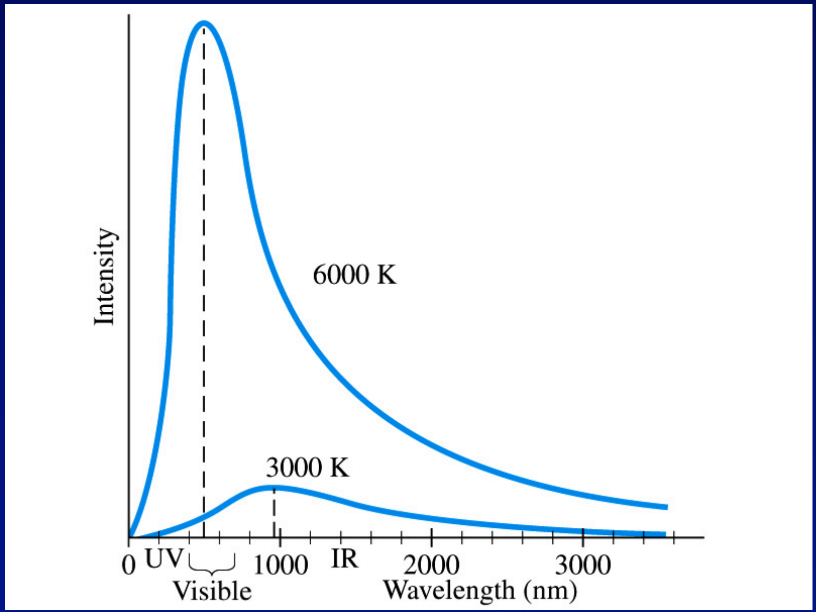
Planck radiation law for blackbody radiation

Predicted:

"ultraviolet catastrophe"



Actual:



Stefan-Boltzmann law: $I = \sigma T^4$

Wien displacement law: $\lambda_m T = 2.90 \times 10^{-3}\ \mathrm{m \cdot K}$

Rayleigh-Jeans (correct at long wavelength): $I(\lambda) = \dfrac{2\pi c k T}{\lambda^4}$

Boltzmann Const.

Planck radiation law

Planck, in order to explain these laws had to resort to an "act of desperation". He assumed the energy of the atoms in the wall were "quantized":

$$E = nhf, \; n = 1, 2, 3, \ldots$$

"Planck's constant": $h = 6.626 \times 10^{-34}$ J·s

Intensity as a function of wavelength, $I(\lambda)$:

$$I(\lambda) = \frac{2\pi hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)}$$

Contains Stefan-Boltzmann, Wien, and Rayleigh-Jeans laws as special cases.

Photoelectric effect

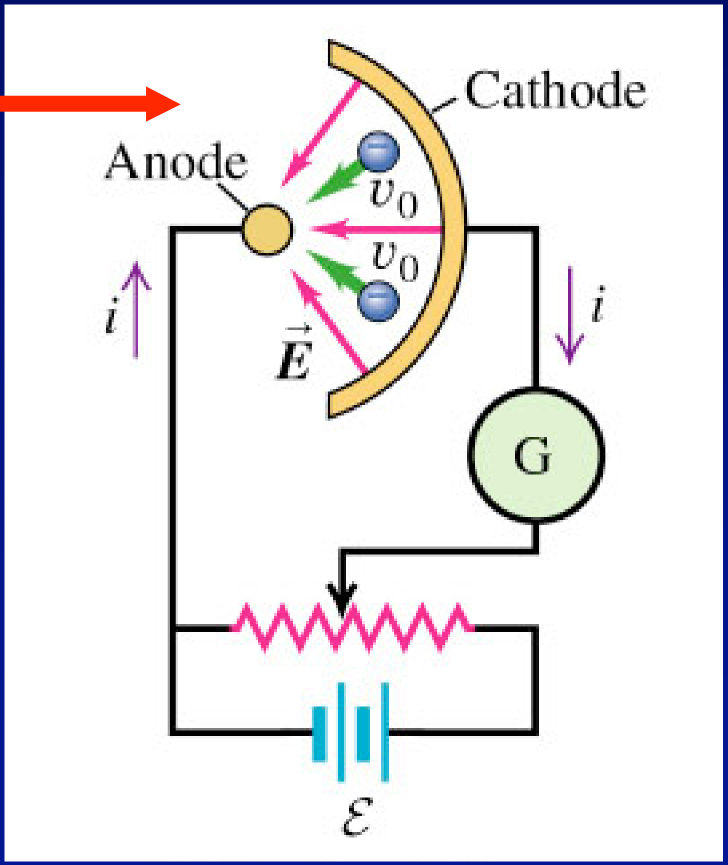
New Topic

Photoelectric effect

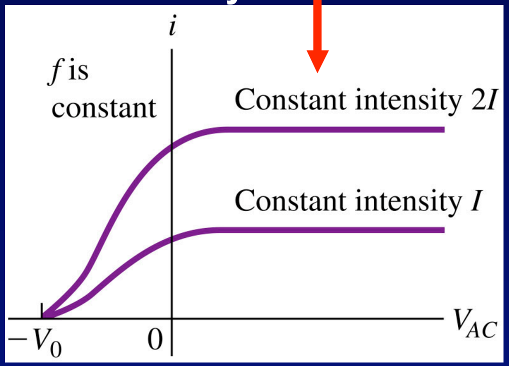
Photoelectric effect observed in 1887

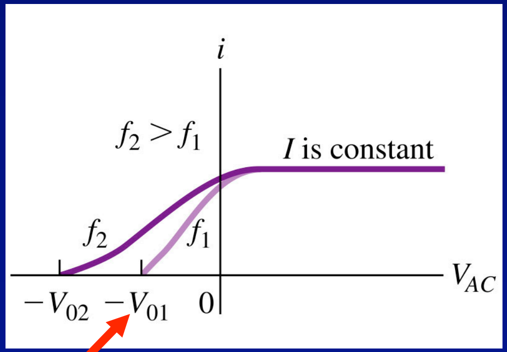
Problem: Electron not discovered until 1897!

Light



Proportional to number of electrons. Notice: V_0 independent of intensity.



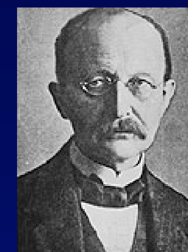


Measures maximum kinetic energy of electrons; V_0 a linear function of f.

Planck and Einstein to the rescue!

$$E = hf = \frac{hc}{\lambda}$$

Planck relation; reinterpreted by Einstein



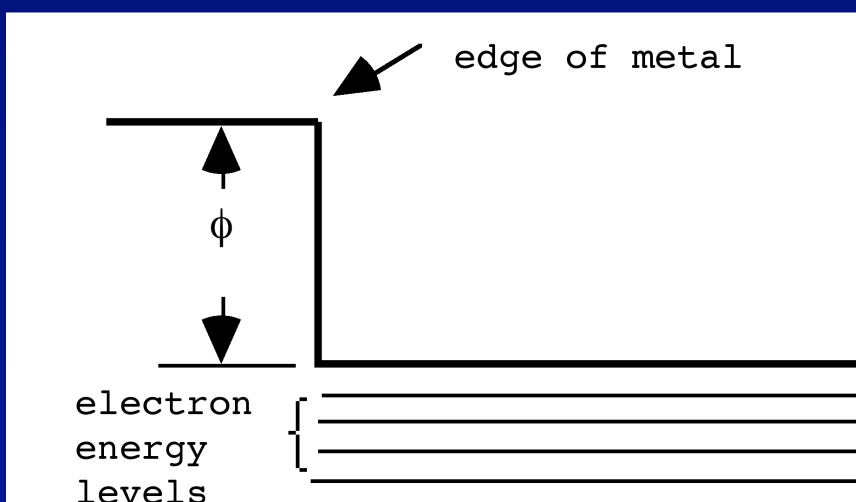
Max Planck, Nobel Prize, 1918)

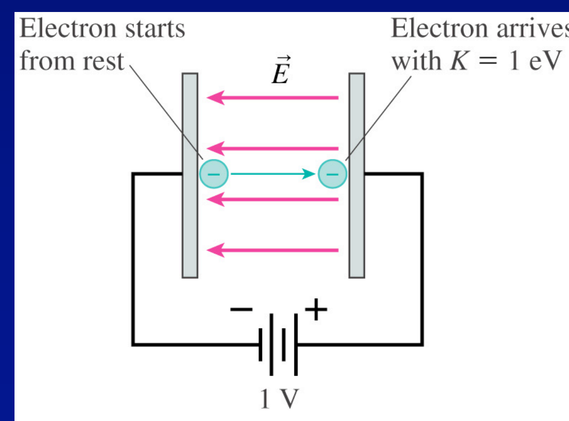
$$K_{\max} = \frac{1}{2} m_e v_{\max}^2 = (-e)(-V_0)$$

A purely "classical" relation

$$eV_0 = hf - \phi$$

ϕ is the "work function", the minimum energy needed to remove an electron



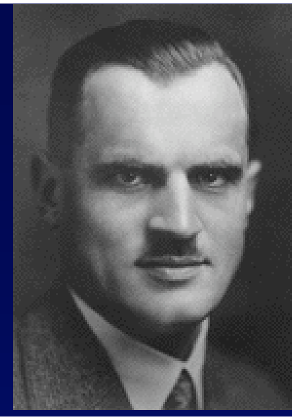


1eV = 1.60 x 10^{-10} J

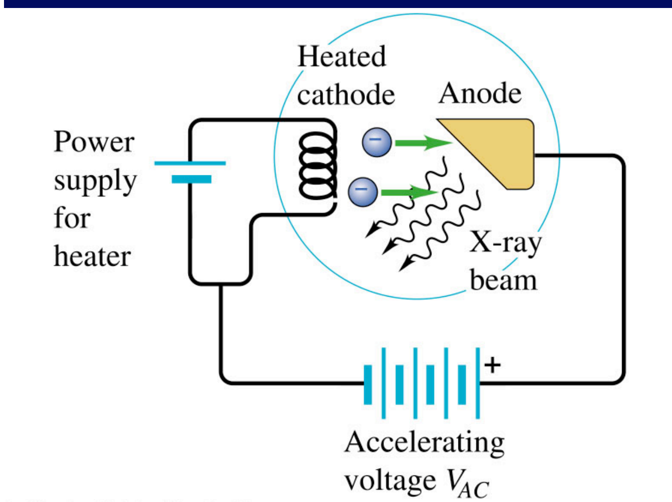
Compton effect

New Topic

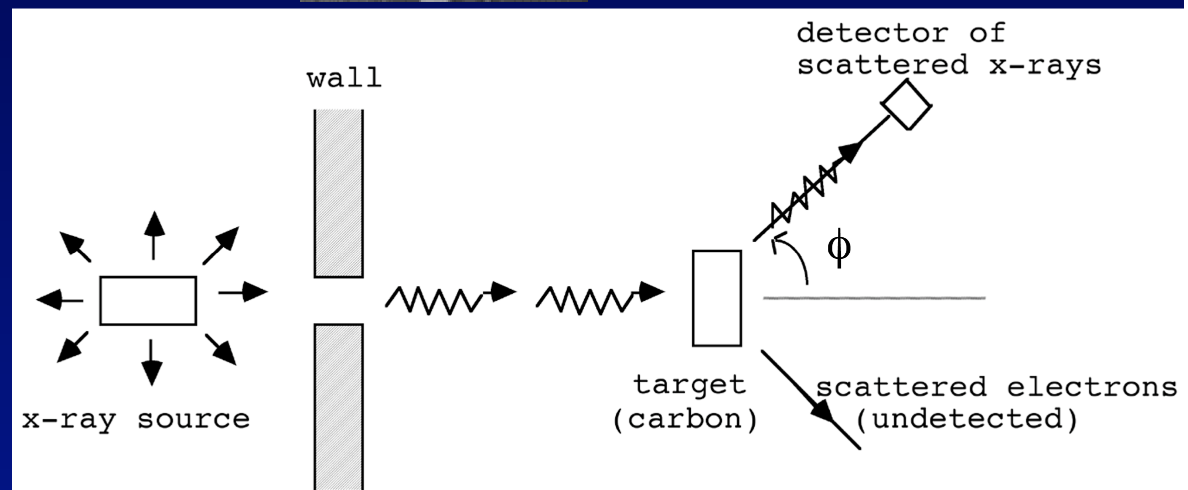
Compton effect



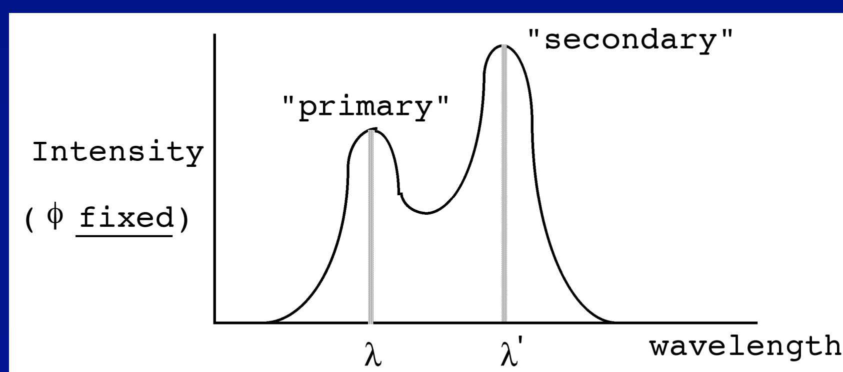
A.H. Compton,
Nobel Prize, 1927.



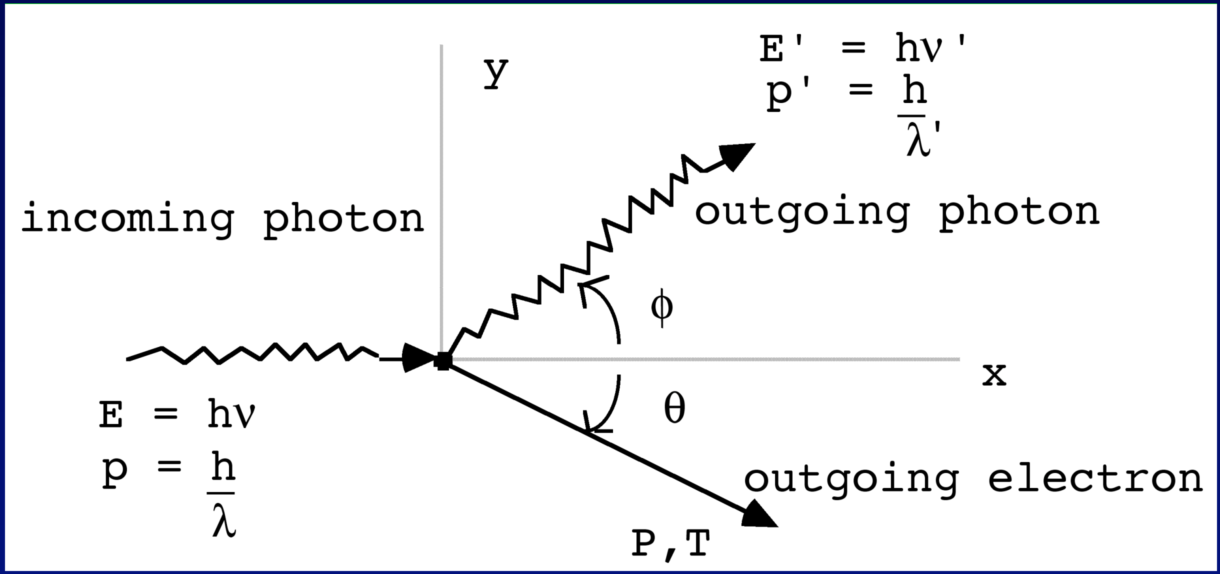
Production



Compton's experiment



Compton effect



Putting $E = pc$ **and** $E = hf$ **together yields**

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

Photons

=> $$\lambda' - \lambda = \frac{h}{mc}(1 - \cos\phi)$$

The wavelength shift calculated holds for the scattering of free electrons, But of course the electrons in an atom are bound to the nucleus. However, X-ray energies are much larger than the atomic binding energy, this treatment is still very accurate.

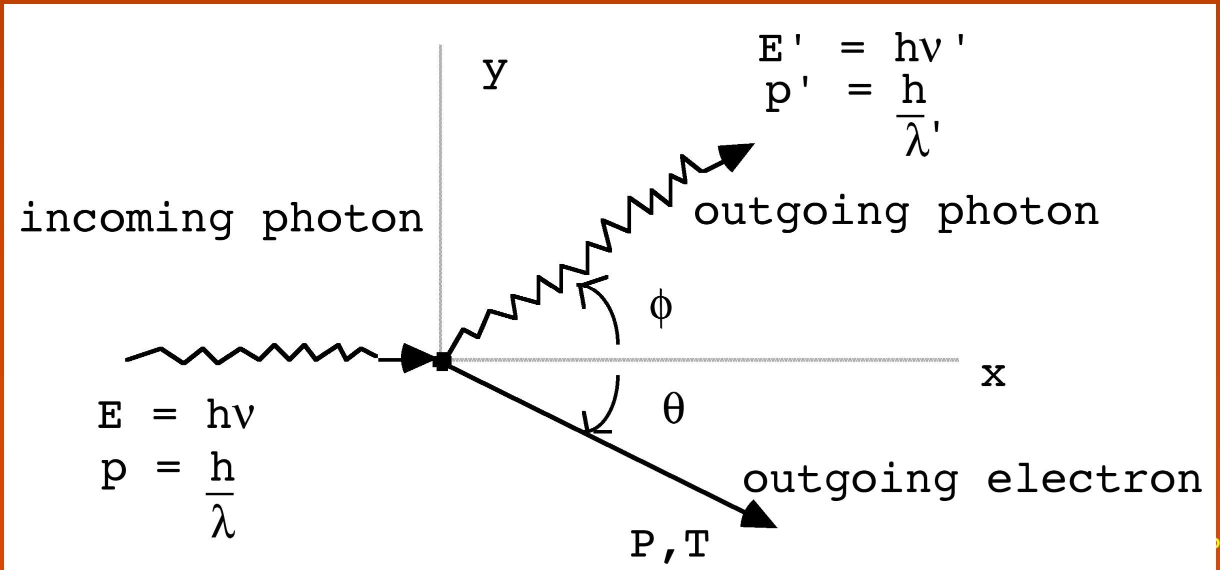
ConcepTest 38.3 Compton scattering

- As a result of Compton scattering, the scattered photon

(1) has the same wavelength as the incident photon

(2) has a longer wavelength than the incident photon

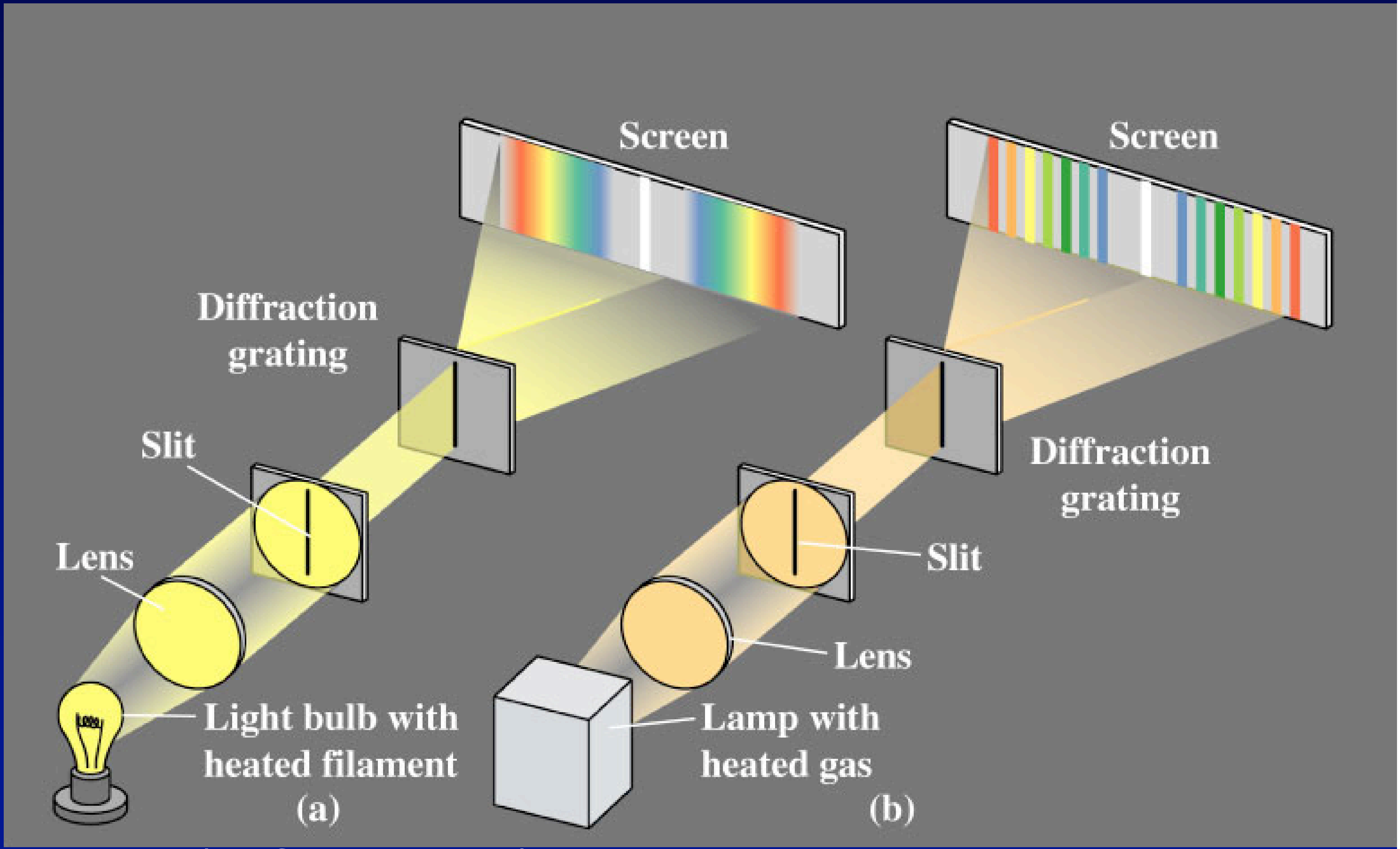
(3) has a shorter wavelength than the incident photon



Line spectra

New Topic

Line Spectra

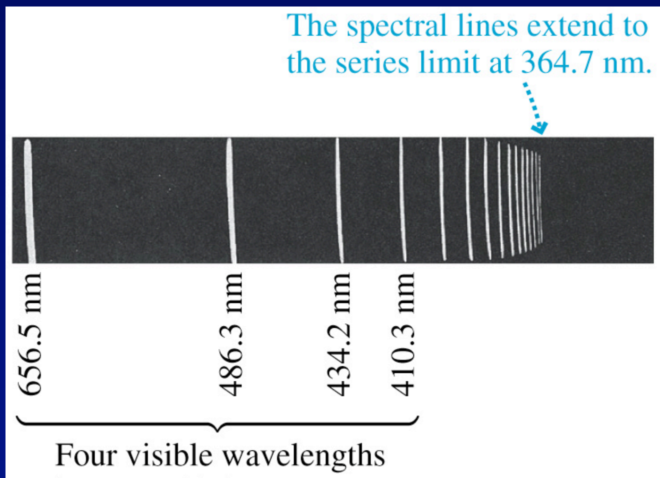


Lamp (all frequencies) Specific gas (line) spectrum

Hydrogen spectrum

$$hf = \frac{hc}{\lambda} = E_\mathrm{i} - E_\mathrm{f}$$

$$E_n = -\frac{hcR}{n^2} \qquad n = 1, 2, 3, 4, \ldots$$

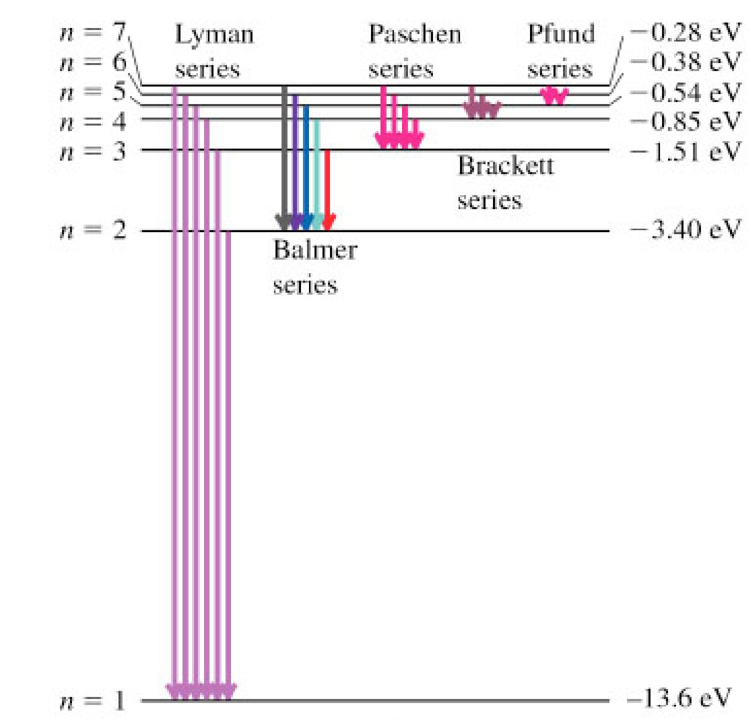


$$\lambda = \frac{91.18\ \mathrm{nm}}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)} \qquad \begin{cases} m = 1 & \text{Lyman series} \\ m = 2 & \text{Balmer series} \\ m = 3 & \text{Paschen series} \\ \quad\vdots & \end{cases} \qquad (24.2)$$

$$n = m + 1, m + 2, \ldots$$

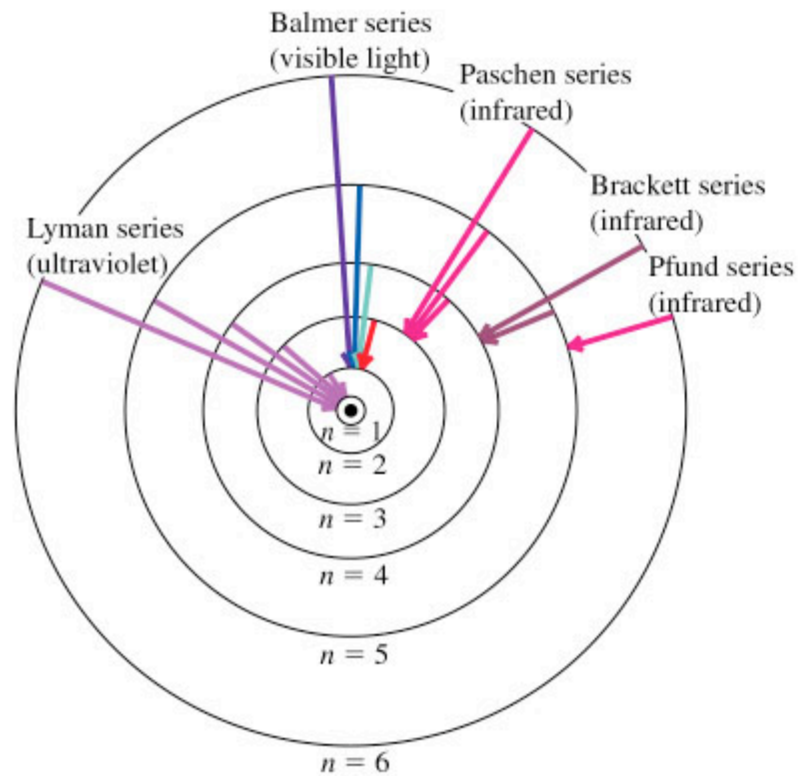
Purely “numerology”.
4 Balmer lines visible;
Lyman in the ultraviolet,
Pashen, etc. in the infrared.

Hydrogen energy levels



(b)

Possible model

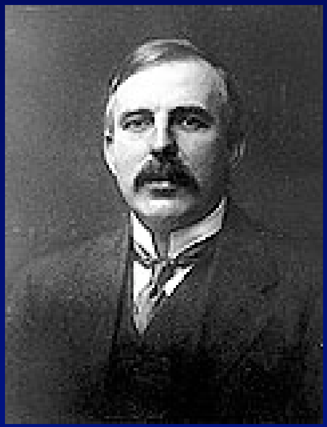


(a)

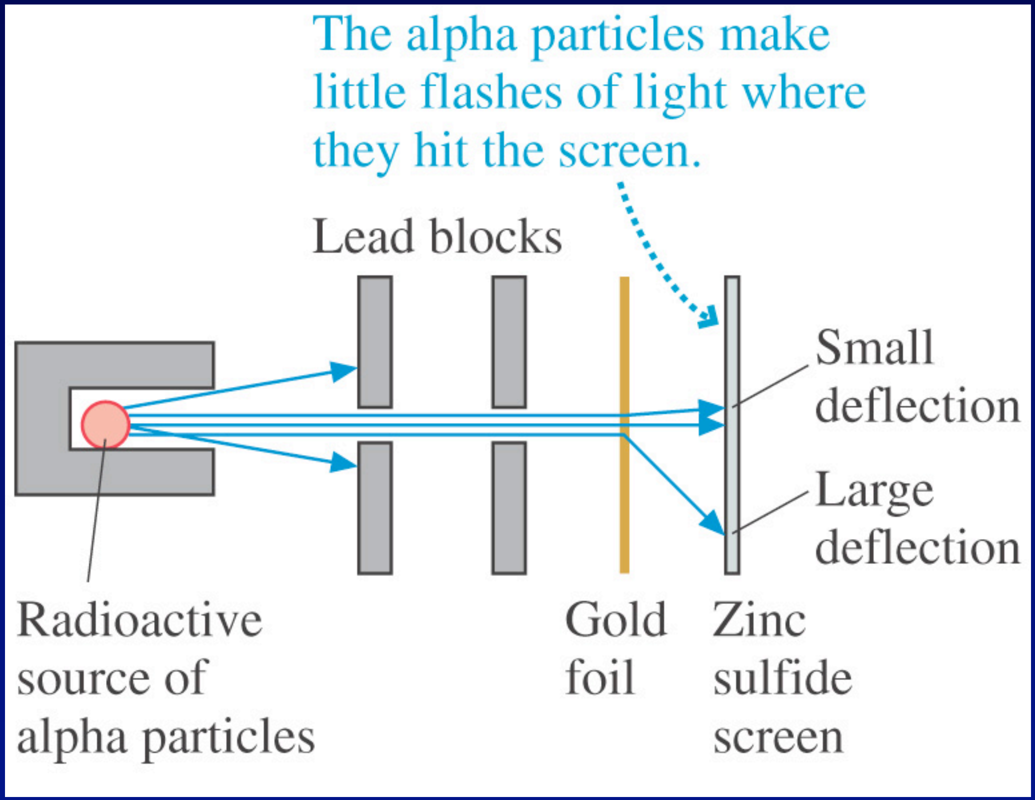
Nuclear physics/Bohr model

New Topic

The first nuclear experiment

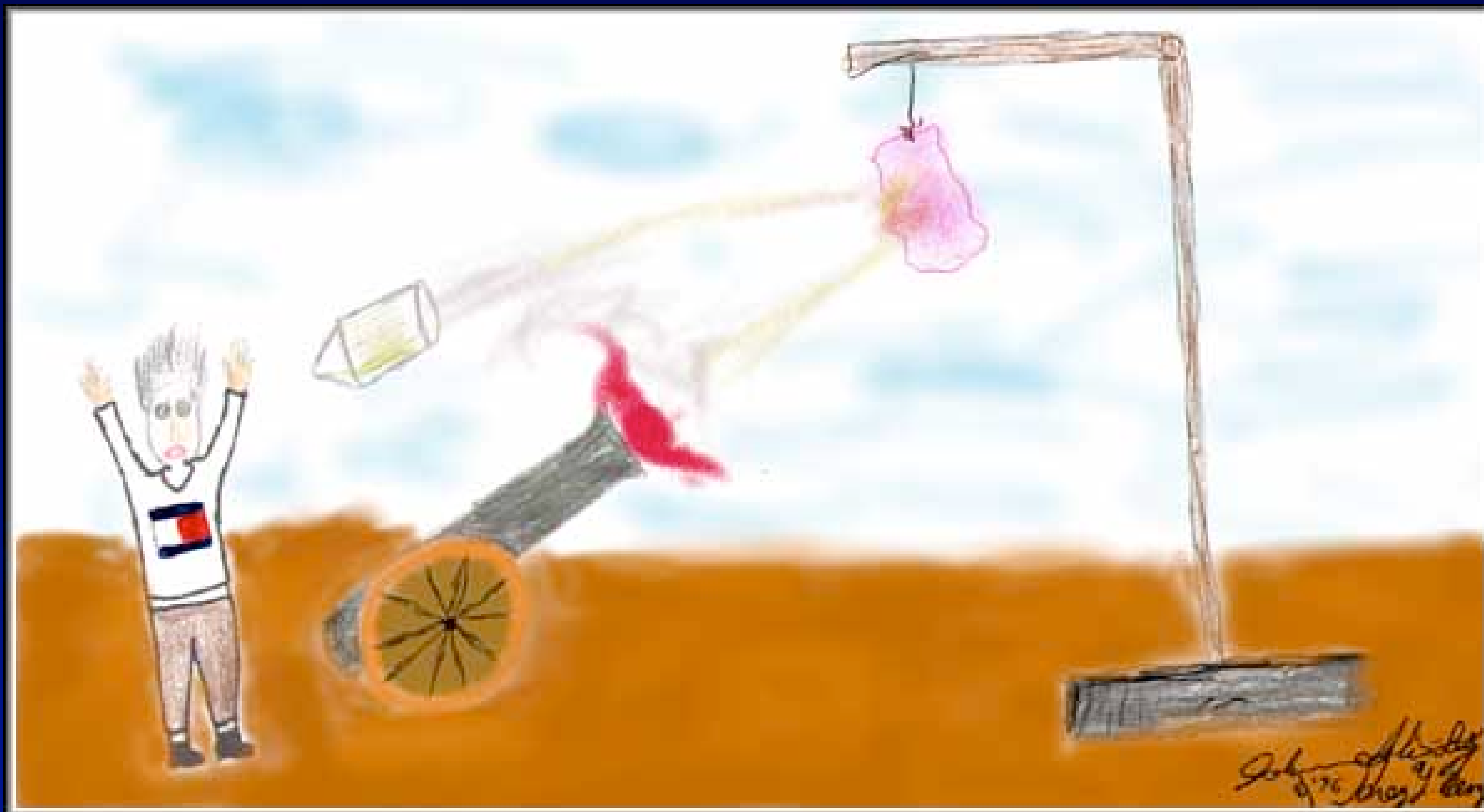


Rutherford (Nobel Prize, Chemistry, 1908)



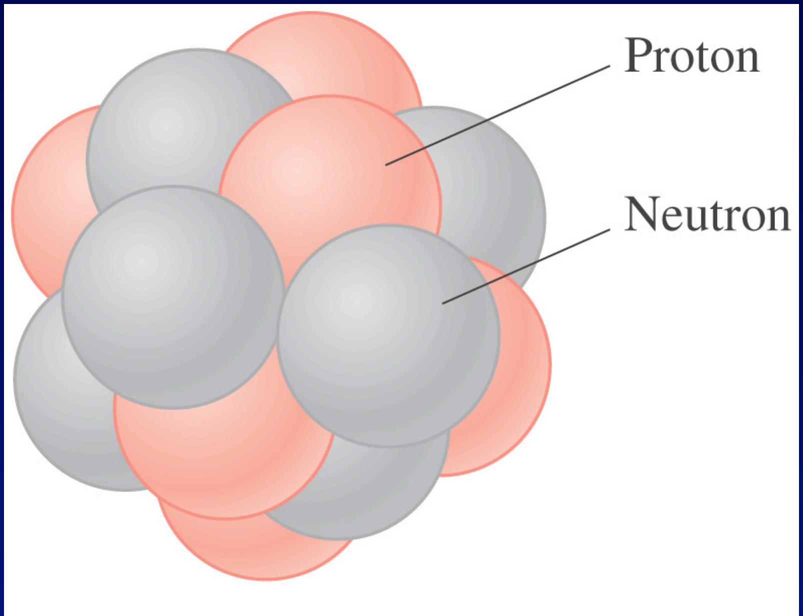
"fruitcake" model

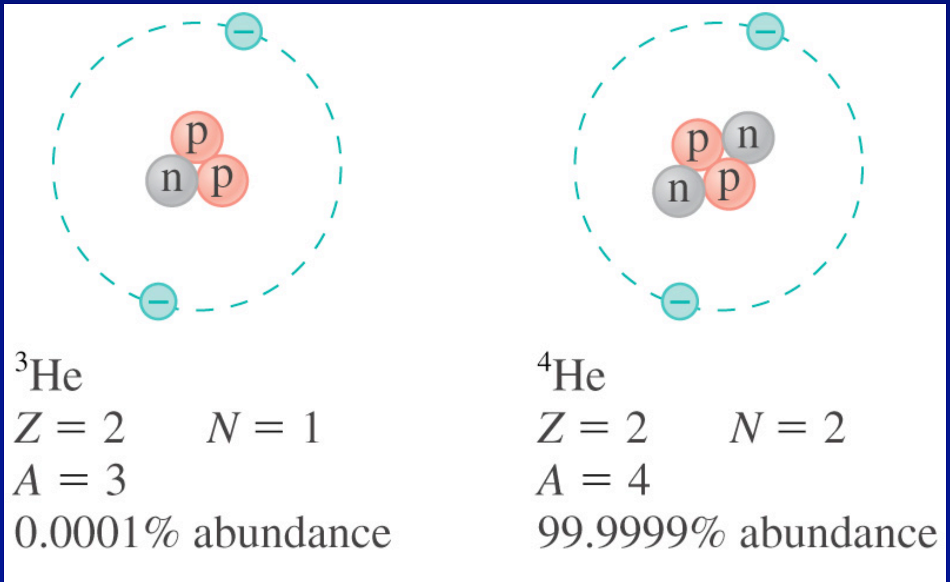
experiment!



“It was almost as incredible as if you had fired A 15-inch shell at a,piece of tissue paper and It came back and hit you.”

The nucleus





Z: "Atomic number"
Number of protons

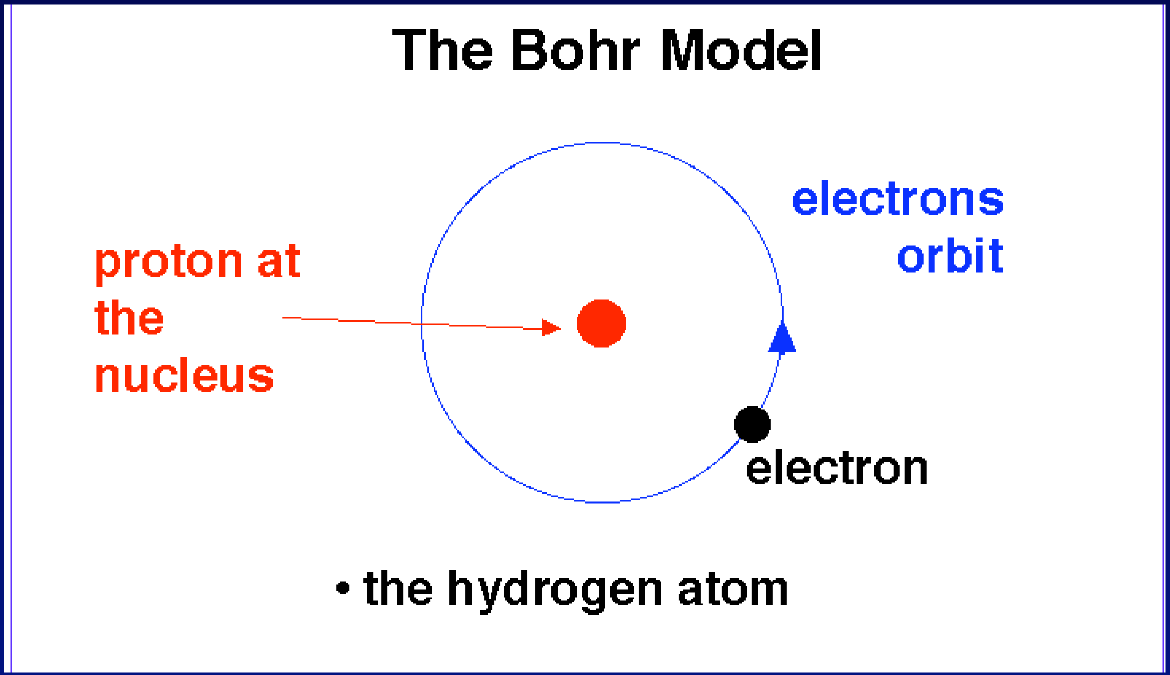
A: "Mass number"
Number of protons and neutrons

Notation: $^A Z$

A = Z + N

Isotopes consist of different nuclei with Same Z, different N.

Bohr model



Combine Newton's inverse square law

$$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_n^2}$$

With Bohr's "ad hoc" assumption

$$L_n = mv_n r_n = n\frac{h}{2\pi}; \quad n = 1, 2, 3, \ldots$$

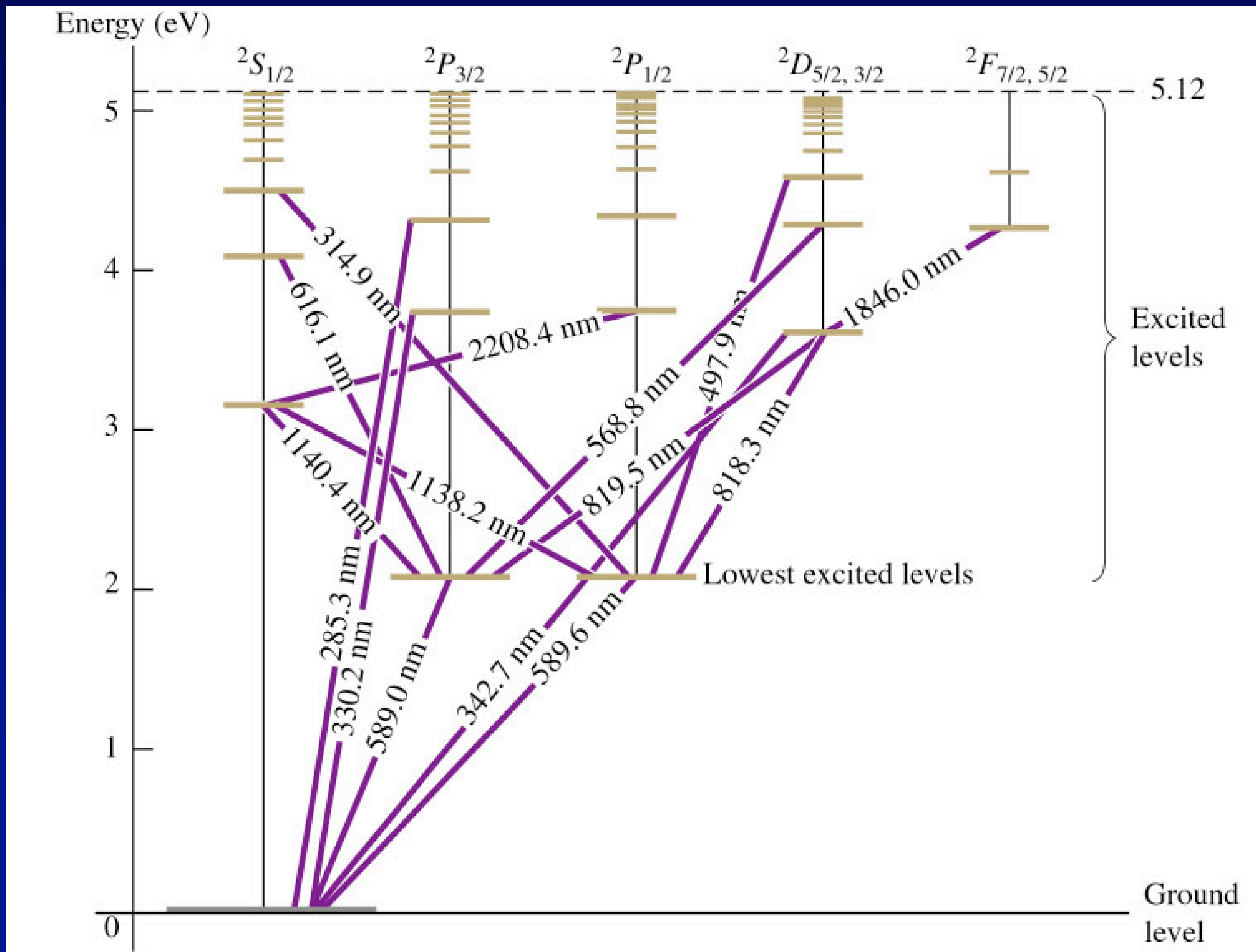
We obtain

"Reduced mass" does even better!

$$E_n = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2}$$

$$\Rightarrow R = \frac{me^4}{8\varepsilon_0^2 h^3 c}$$

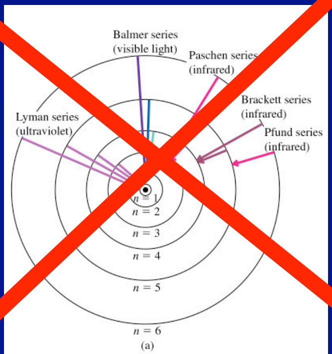
Energy levels are complex! (Sodium)



Bohr model is wrong!

N. Bohr, Nobel Prize 1922.

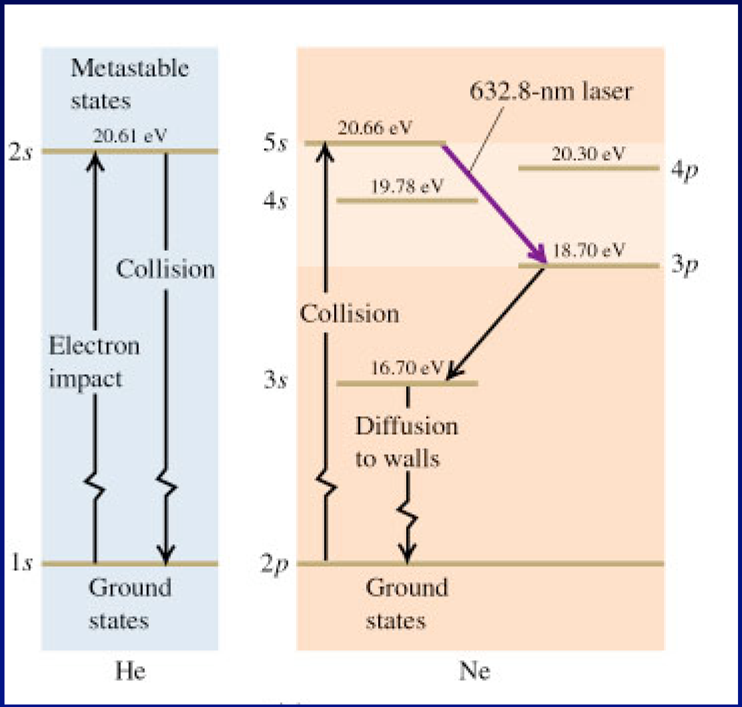
Although the Bohr model was correct in predicting the energy levels of hydrogen, it is a patchwork classical/quantum beast. If one attempts to apply it to other atoms, there are persistent discrepancies. It also makes a wrong prediction about hydrogen: that it has a magnetic moment in the ground state, $L_1=h/2\pi$. The angular momenta ARE quantized, but the ground state has $L_1 = 0$. The picture of orbiting electrons, essentially like planets around the sun, is simply wrong!!

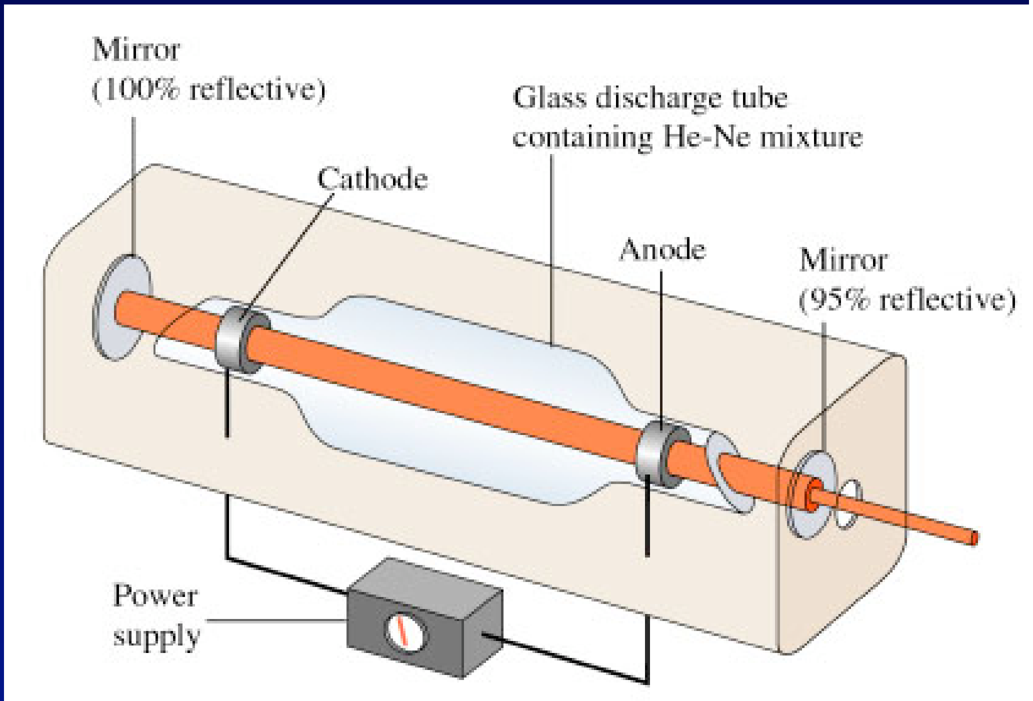


Lasers

New Topic

Lasers





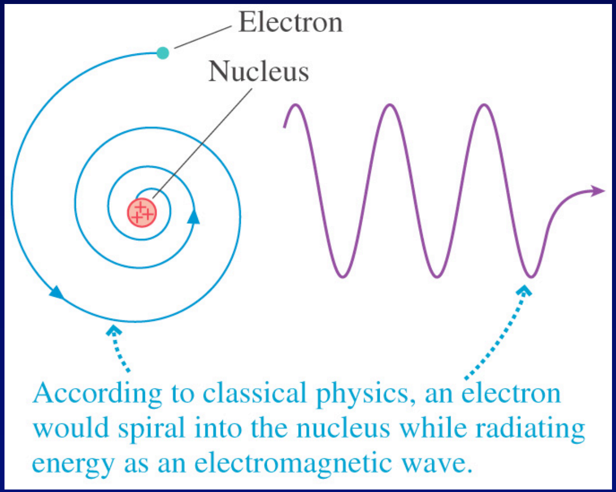
Relevant concepts: population inversion, metastable state, stimulated emission, optical cavity

For types of lasers, click here

Quantum mechanics

New Topic

On the road to Quantum Mechanics

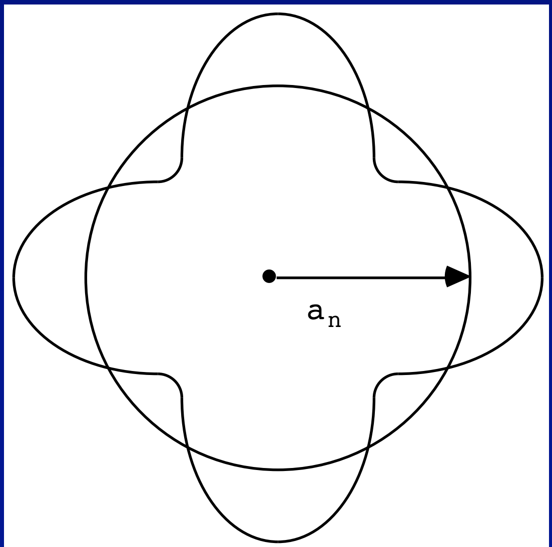


The relation (photons as particles)

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

also applies to electrons (particles as waves) and all other particles. Due to L. DeBroglie (1925).

=> Wave-particle duality



$\Psi(x,y,z,t)$ is the particle "wavefunction". Schrödinger equation:

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\left(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2}\right)$$

=> Principle of complimentarity