The quantum view of the world 1

The beginning of quantum mechanics

Modern physics for engineers

David Miller

Puzzles for classical physics

Statistical mechanics

- Ideas of statistical mechanics were emerging in the 1870s
  - starting with James Clerk Maxwell’s and Ludwig Boltzmann’s work on thermal distributions
    - which could explain some properties of gasses
      - and, increasingly, other phenomena, such as specific heat

Statistical mechanics

- Boltzmann's work started a meaningful interpretation of entropy
  - through the statistics of the occupation of possible states
- Such theories presume there are discrete states for a system
  - Counting states leads to the statistical ideas of entropy
    - but there was no physical basis for arguing that there should be such discrete states

Spectroscopy of hydrogen

Spectroscopy showed remarkable structure in the colors of light emitted by excited hydrogen

Johann Balmer in 1885 noticed that

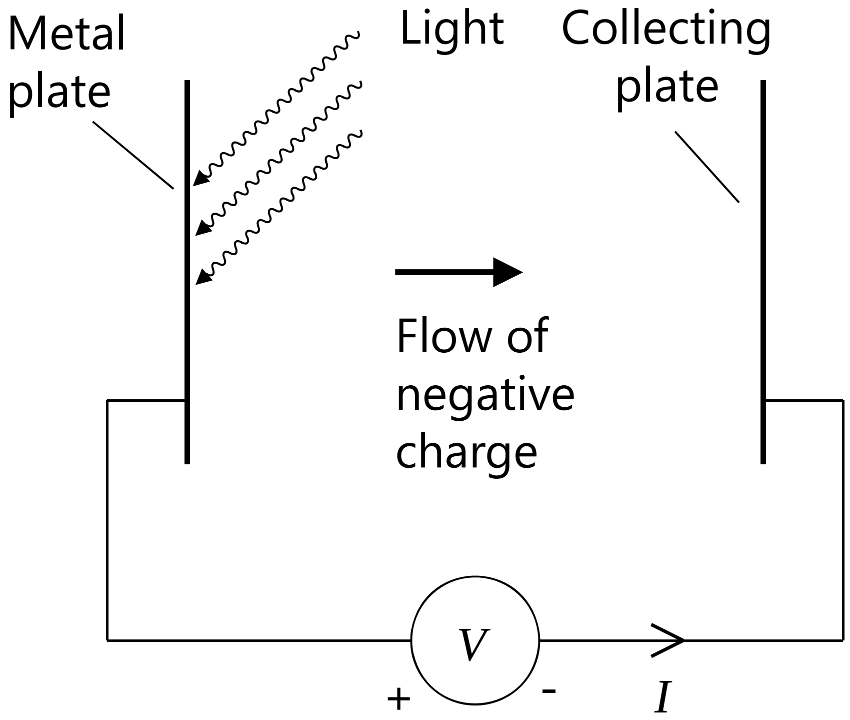
a simple expression could predict the wavelengths of the spectral lines of hydrogen

as measured by Ångström

in what is now called the Balmer series of lines

Photoelectric effect

- Shining ultraviolet light on the metal plate here
  - gives a flow of negative charge (Hertz, 1887)
- Classical physics might explain why absorbing energy in the metal leads to more current
  - it does not explain why the light's wavelength matters



Light

Color of hot objects

It has been well known for thousands of years that hot objects emit light

- Blacksmiths could effectively gauge temperature by color
- Flames were the major source of light at night
  - but we did not understand why hot objects emit light
    - nor their color

Incandescent light bulbs

- Following many experiments throughout the 19th century
  - carbon filament incandescent light bulbs became practical by about 1880
    - as marketed by Thomas Edison and others
- Practically these were limited by filament temperature and lifetime

bulb at Livermore fire station, running since 1901

Incandescent light bulbs

But there was no good model
- for how much light could be emitted
  - or what color it would be

though it was understood
- from Kirchhoff's Law of Thermal Radiation
  - that the most absorbing "black body"
    - would be the best emitter

bulb at Livermore fire station, running since 1901

Quantum and light bulbs

In 1887, the German government
- stimulated in part by Werner von Siemens

founded the Physikalisch-Technische Reichsanstalt (PTR)
- the Imperial Institute of Physics and Technology near Berlin

bulb at Livermore fire station, running since 1901

Quantum and light bulbs

One priority for PTR -

understand light emission from hot bodies

for better light bulbs

Kirchhoff's Law of Thermal Radiation already tells us that

a body that perfectly absorbs light will be the best possible thermal emitter of light

a "black body"

bulb at Livermore fire station, running since 1901

Quantum and light bulbs

By the late 1890's

- very precise measurements were being made
  - of the emission spectrum of a black body

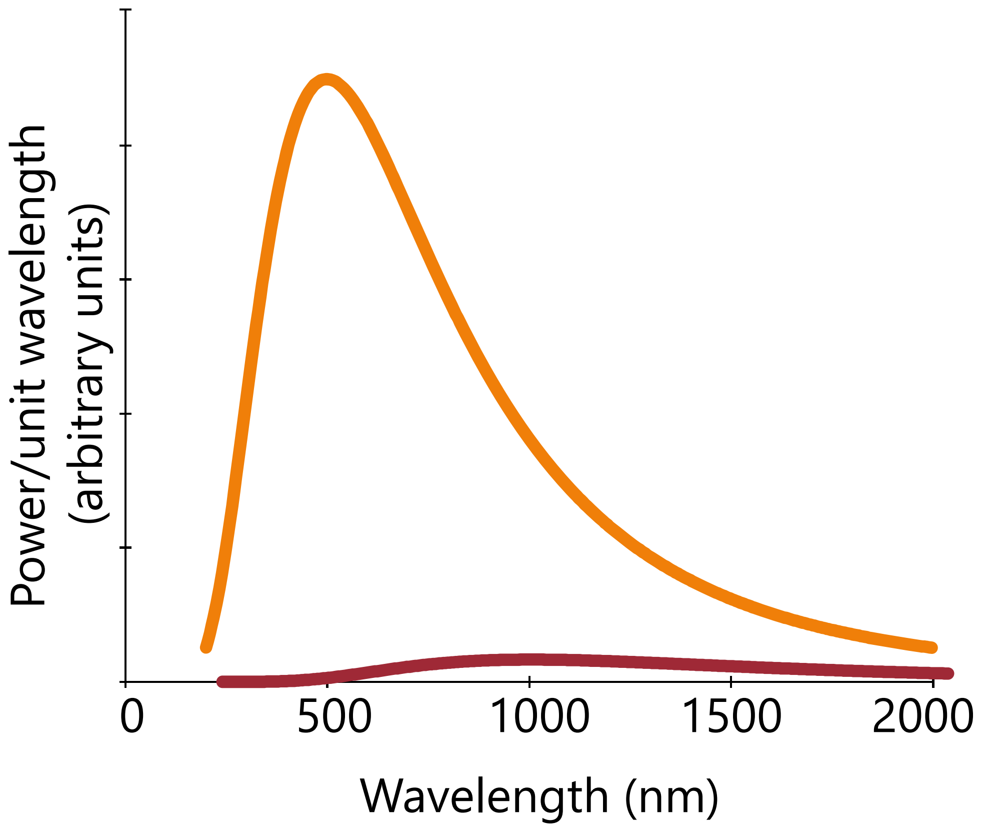
But no-one knew where its universal shape came from

- or how to explain it mathematically or physically

bulb at Livermore fire station, running since 1901

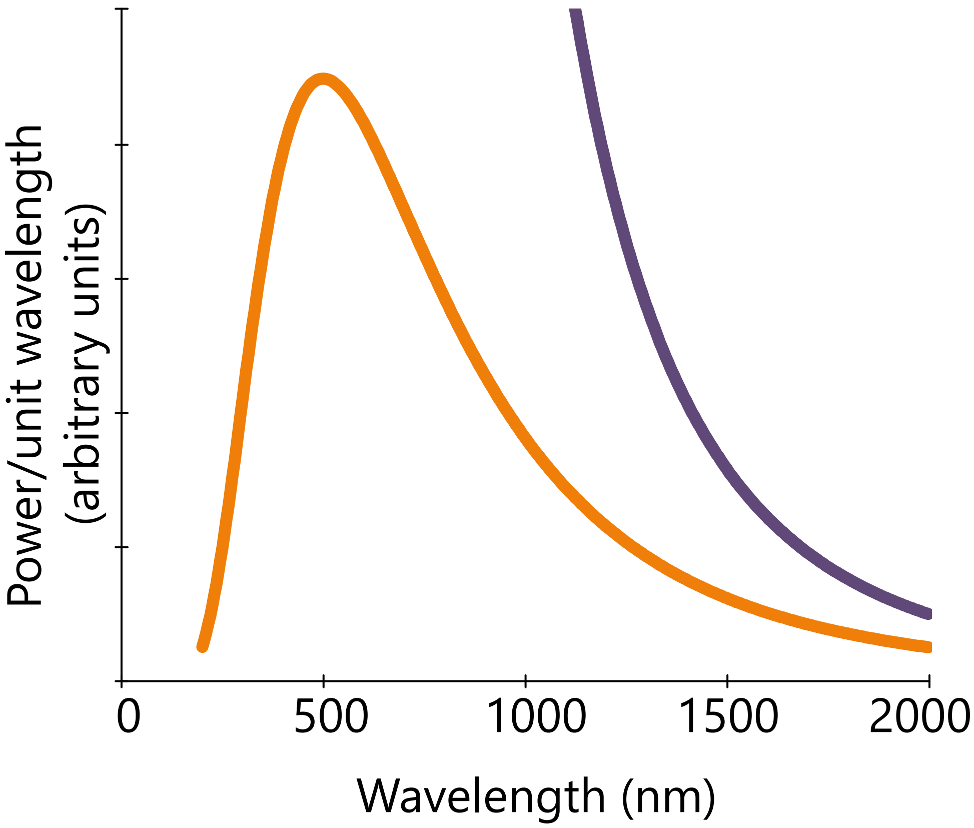
Black-body spectrum

- Output power (per unit wavelength)
  - For a black body at 5800K
    - approximately like the sun
  - For a black body at 3000K
    - approximately like an incandescent light bulb
- But models based on the thermal physics of the time
  - did not work



Black-body spectrum

The Rayleigh-Jeans classical model gives the "ultra-violet catastrophe" showing no good explanation for the shape of the curve



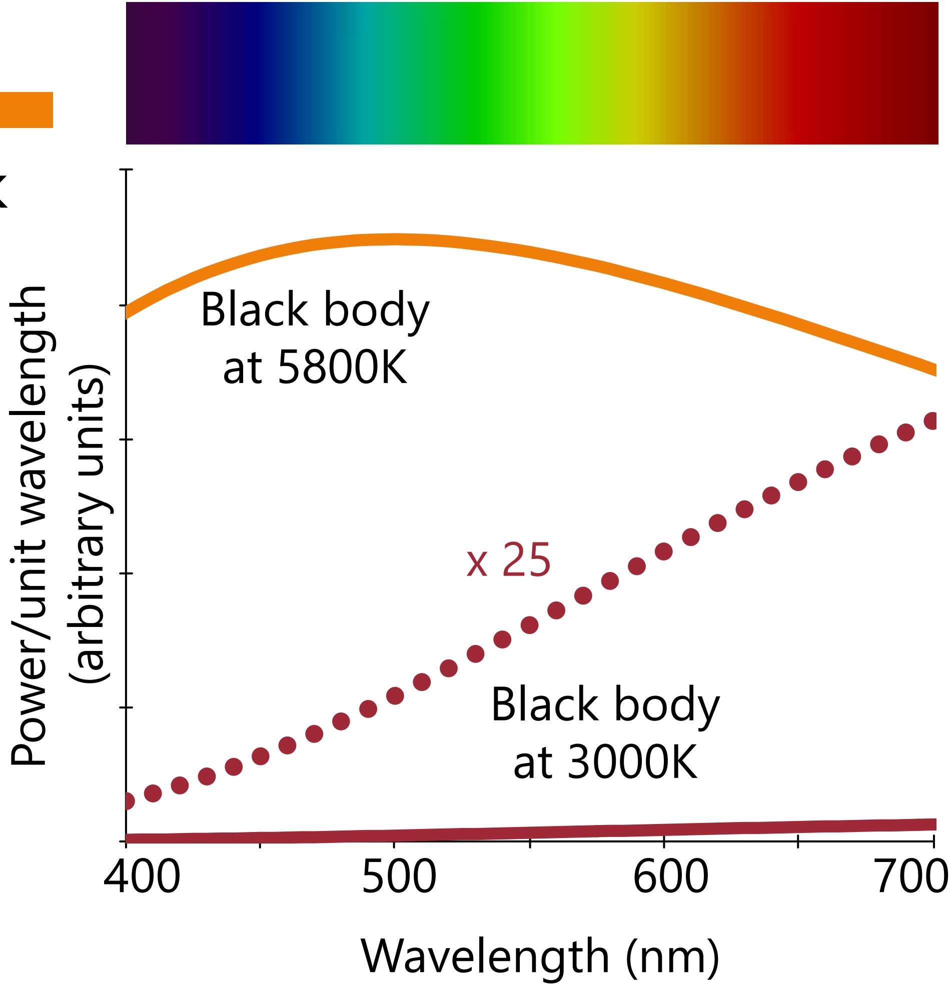
Black-body spectrum

An expanded view of the black body spectrum

- at 5800 K and
- at 3000 K

in the visible range of the spectrum

- shows the difficulty of making efficient thermal emitters of visible light
  - at practical temperatures



Planck's proposal

Max Planck, then a professor in Berlin

in 1900 proposed both a formula and

a derivation using one "ad hoc" assumption

Light is emitted in quanta of energy $E = hf$

where f is the light's frequency in Hz (hertz)

and h is Planck's constant $h = 6.62606957 \times 10^{-34}$ Js

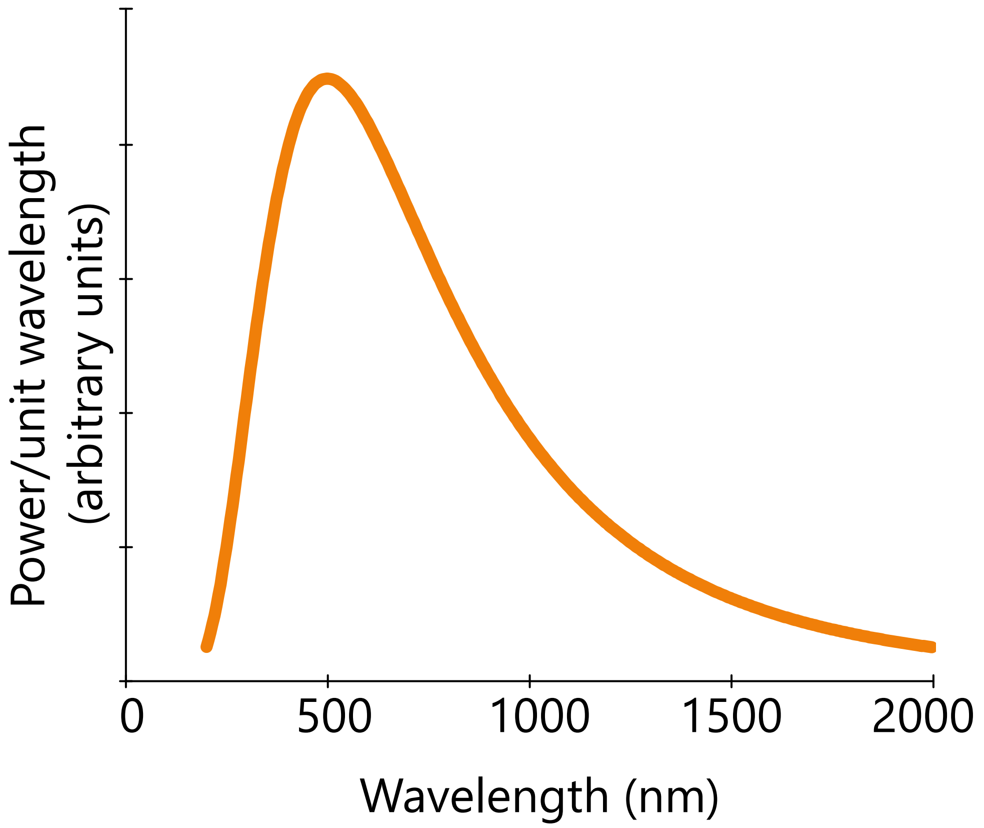
or, equivalently $E = \hbar\omega$

where $\omega = 2\pi f$ is the "angular frequency"

and "h bar" is $\hbar = 1.054571726 \times 10^{-34}$ Js

Black-body spectrum

- Planck's formula agrees very well with observed spectra
  - Note, though, that Planck did not propose the photon
    - That would apparently have contradicted the very successful wave theory
      - based on Maxwell's equations
- He just proposed *emission* in quanta



The photon, emission and absorption

- Albert Einstein in 1905 proposed the photon
  - to explain the photoelectric effect
- He later extended the quantum theory of light in 1917
  - using this photon idea
    - and elegantly rederiving Planck's black-body spectrum

The photon, emission and absorption

- In this work he also explained light emission and absorption by atoms
  - relating
    - absorption
    - spontaneous emission
      - the most common light emission, as in light bulbs
    - and his new idea of stimulated emission
      - the process seen in lasers
  - in his “A and B coefficient” argument

Wave-particle duality

His proposal of the photon introduces
  wave-particle duality

How can light simultaneously be
  a wave and a particle?

This is arguably not a problem for quantum mechanics, but we must
  avoid bringing along all the classical attributes of particles and waves

The wave-particle duality of light is verified trillions of times a day
  in optical fiber communications

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Electrons and atoms

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The early quantum experiments on atoms

Early experiments on the structure of the atom

- "Cathode rays" in evacuated tubes
  - culminating in Joseph ("J. J.") Thomson's 1897 work
    - showed they were very light particles with negative charge
      - what we now call electrons
        - that were components, in some way, of atoms
- Ernest Rutherford in 1911
  - by scattering alpha particles with gold foil
    - concluded atoms had a very small charged nucleus
      - much smaller than the atom itself

Hydrogen atom emission spectra

Hot hydrogen emits light

in a set of spectral lines

The Balmer series

is a set of lines in the visible spectrum

The Bohr model of the hydrogen atom

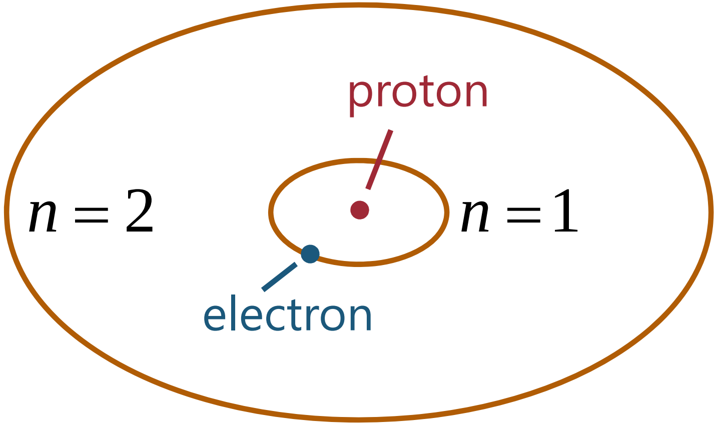
Bohr model of the hydrogen atom

A small negatively charged electron

orbits a small positively charged core (the proton)

like a planet round a sun

but with electrostatic attraction



Key assumption (Neils Bohr, 1913)

angular momentum is "quantized" in units of Planck's constant, h, over 2π

$$\frac{h}{2\pi} \equiv \hbar$$

"h bar"

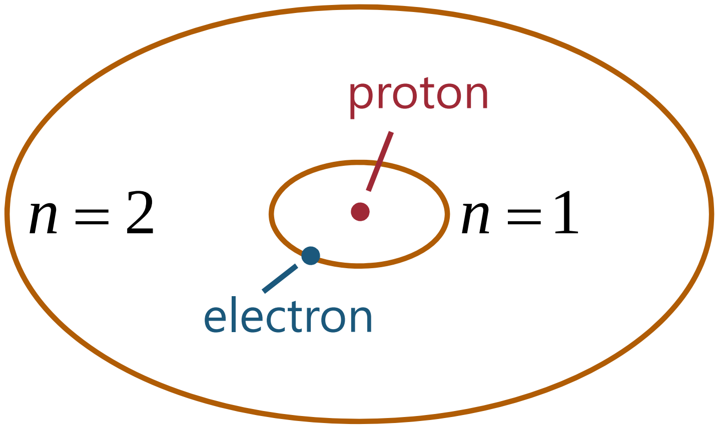
Bohr model of the hydrogen atom

It correctly predicts the energy levels of the hydrogen atom

$$E_H(n) = -\frac{Ry}{n^2}$$

where Ry is the Rydberg energy

$$Ry \simeq 13.6 \text{ eV}$$



The electron-volt (eV) energy unit

$$1\,\text{eV} \equiv |e|\,\text{J} \simeq 1.602\,176\,565 \times 10^{-19}\ \text{J}$$

is the energy to move an electron through 1 V

Bohr model of the hydrogen atom

The model does give the photon energies of the spectral lines

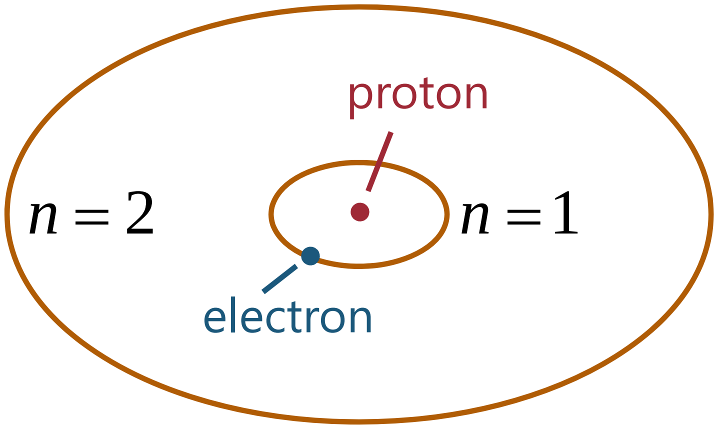
as the separations of the energies of the different orbits

The relation between wavelength λ and frequency f for light is $\lambda = \frac{c}{f}$

where $c = 299\ 792\ 458\,\mathrm{m/s}$

so photon energy is

$$E = hf = hc / \lambda$$



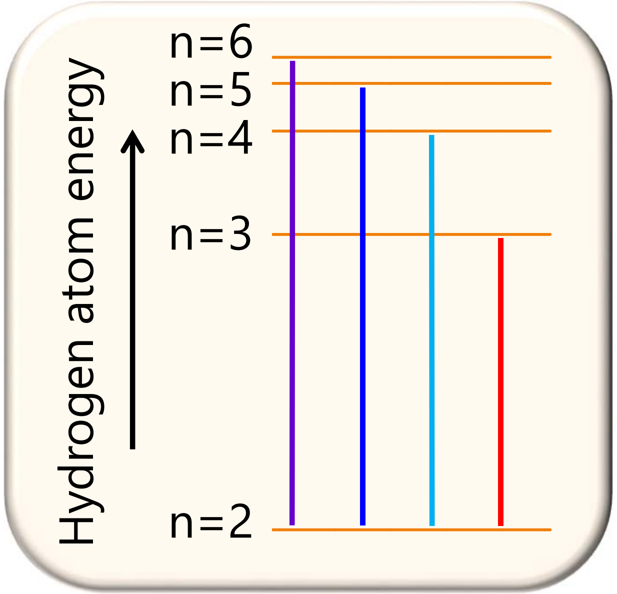
Hydrogen atom emission spectra

H-delta
410.2 nm
n=6 to
n=2

H-gamma
431.4 nm
n=5 to
n=2

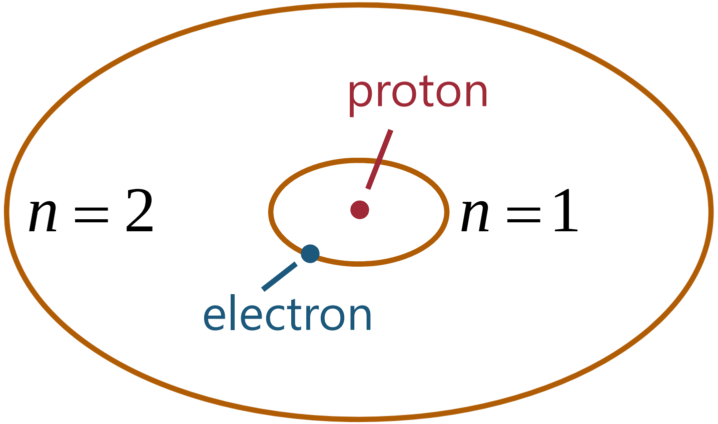
H-beta
486.1 nm
n=4 to
n=2

H-alpha
656.3 nm
n=3 to
n=2



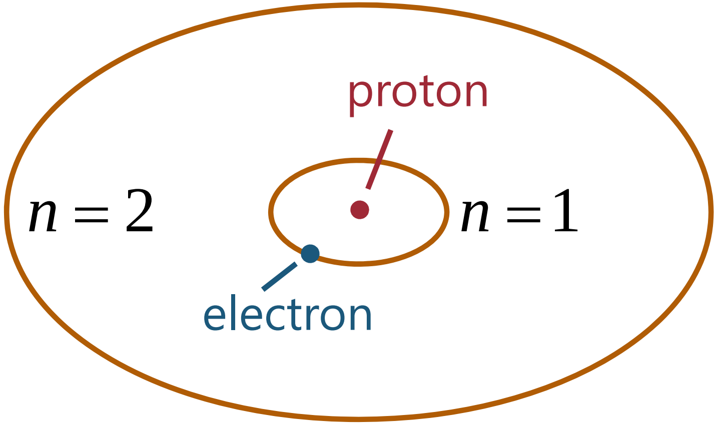
Bohr model of the hydrogen atom

The model
- successfully introduces Planck's constant into the theory of matter
  - and gets the approximate size of the atom right
    - The characteristic size is the Bohr radius ~ 0.05 nm
      - 0.5 Å (ångströms)
- So the hydrogen atom is about 1 Å in diameter



Bohr model of the hydrogen atom

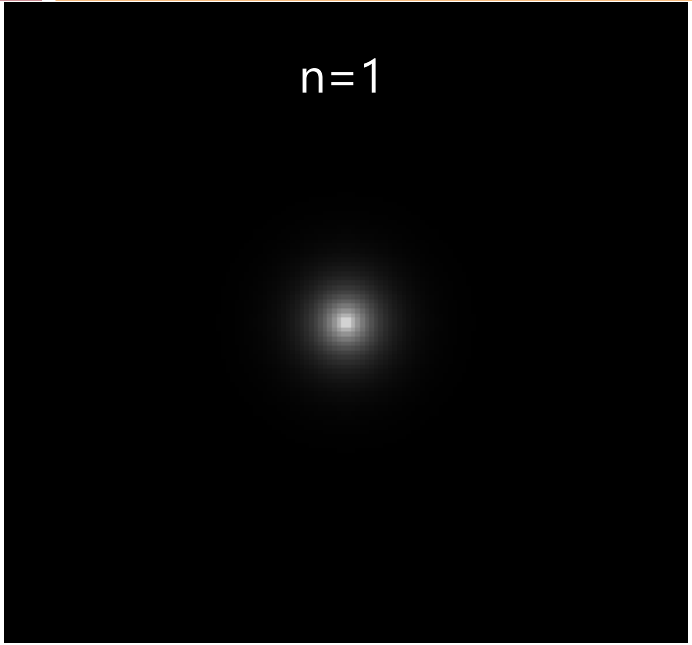
- The model does not get the angular momentum quite right
  - though the quantization in $\hbar$ units remains very important
- The model appears to predict the atom would radiate all the time
  - from the orbiting electron
- The atom does not "look" like this
  - It is not a small "point" electron in a classical orbit

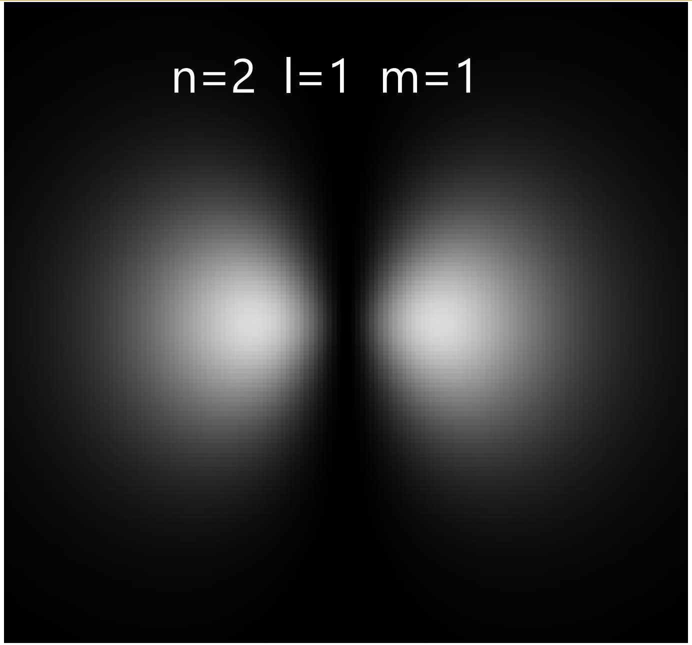


$$\frac{h}{2\pi} \equiv \hbar$$

"h bar"

Hydrogen atom orbitals





Electron charge density in hydrogen orbitals is actually more like these pictures

The electron is not a moving point particle