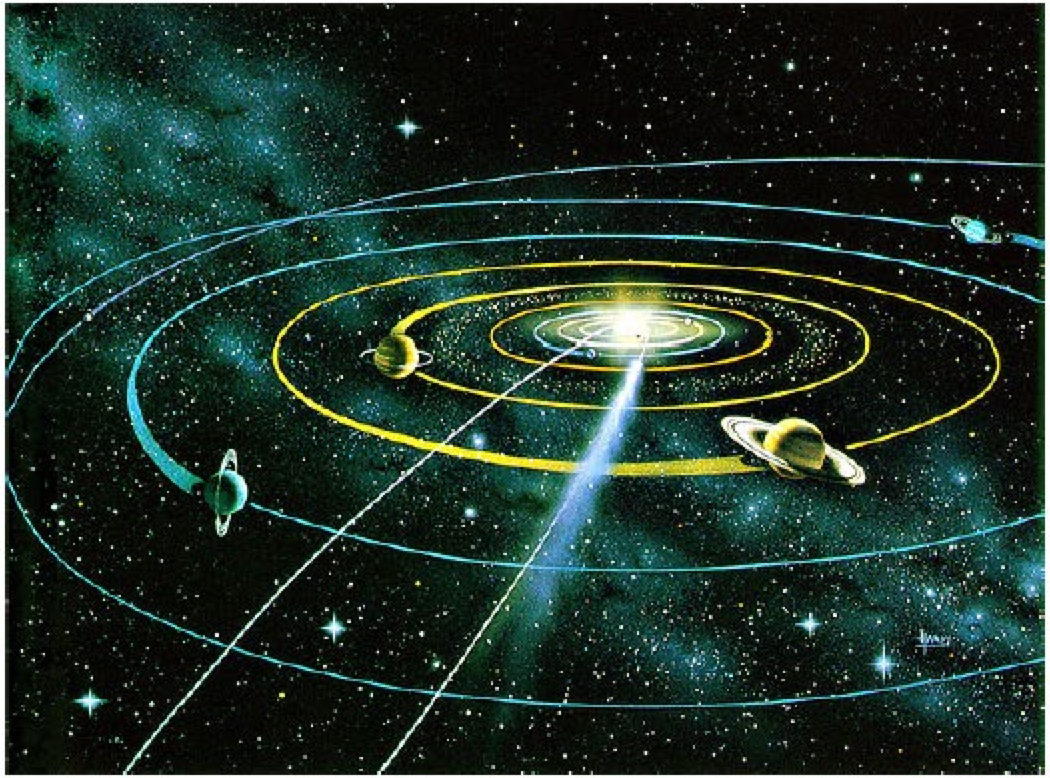
2. Early history of quantum mechanics

Classical mechanics

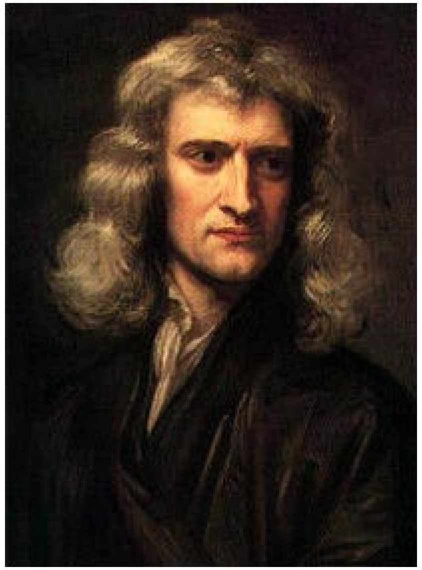


Planetary orbits

Around 1610: Johannes Kepler formulated the laws of planetary orbits.

(Slides courtesy of Asa Larson, Stockholm University)

Classical mechanics



1687 Isaac Newton

"Philosophiae Naturalis Principia Mathematica"

$\Rightarrow$ Newton's laws of motion

Lagrange, Laplace Hamilton

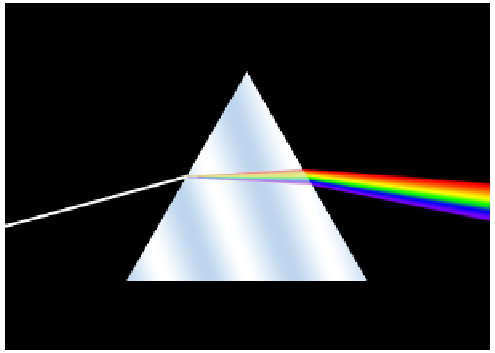
$\Rightarrow$ Mathematical toolkit

Deterministic worldview

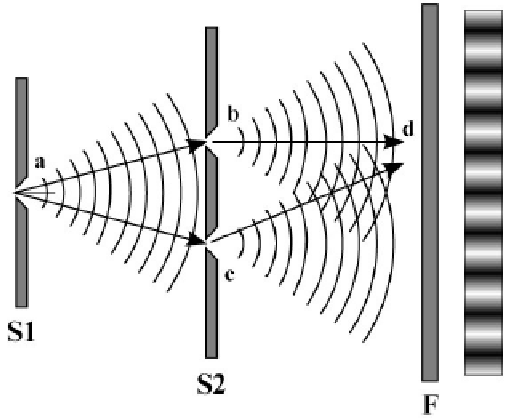
$$x(0) = \ldots, v(0) = \ldots$$
$$\Rightarrow x(t) = \ldots, v(t) = \ldots.$$

Light

1690 Newton



1801: Young: Interference ⇨ wave nature of light



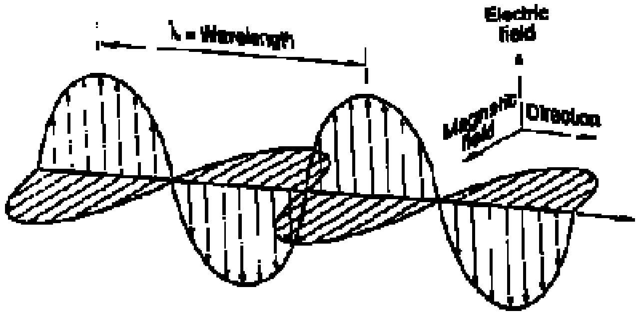
1873: James Clerk Maxwell's theory of electromagnetism

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$



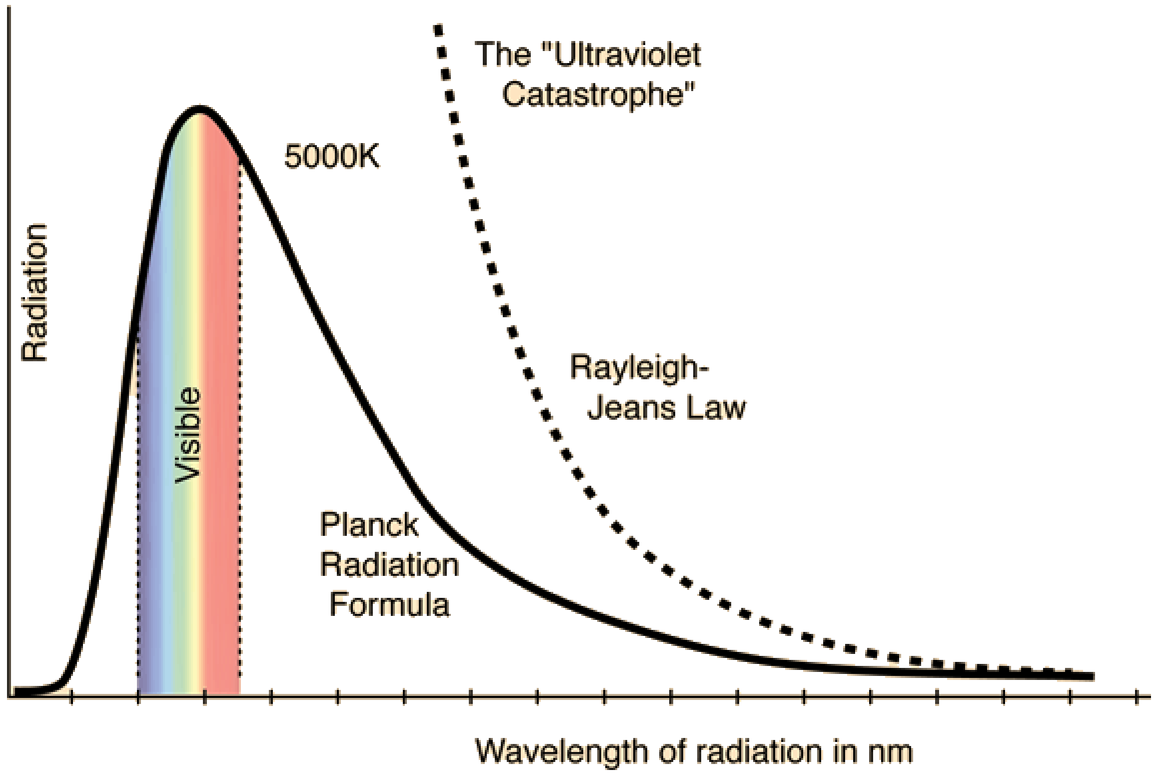
Lord Kelvin, around 1880

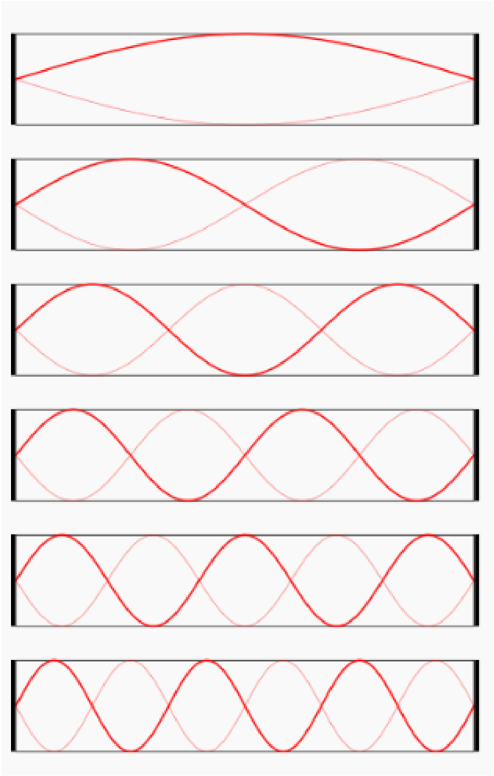
''There is nothing new to be discovered in physics now, All that remains is more and more precise measurement.''

Problems around 1900

1. *Black-body radiation UV-catastrophe*
2. *Photoelectric effect*
3. *The linespectrum of atoms*

1. Black-body radiation, UV-catastrophe

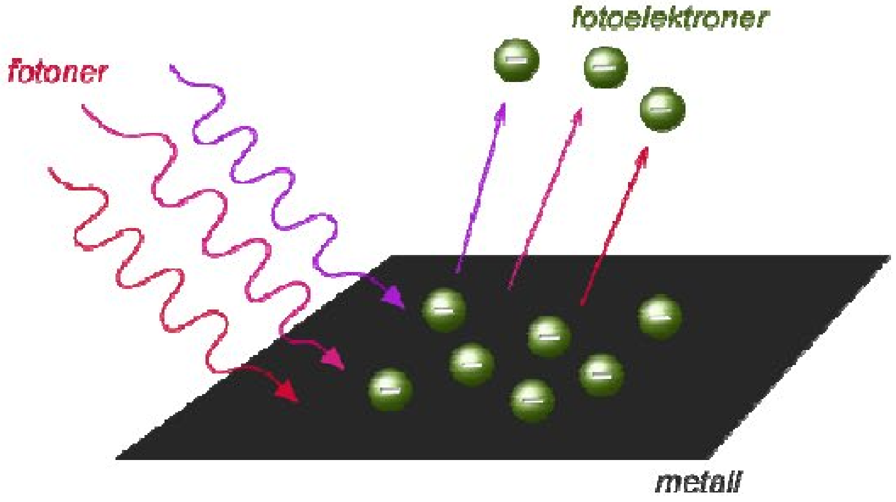




Theory of black-body spectrum does not agree with experiment!

number of electromagnetic modes in a 3-dimensional cavity, per unit frequency, is proportional to the square of the frequency

2. Photoelectric effect



1887 Experimental measurements by Hertz & Hallwachs: Negative charges are released upon radiation of UV light.

1899: Lenard: photo-electrons

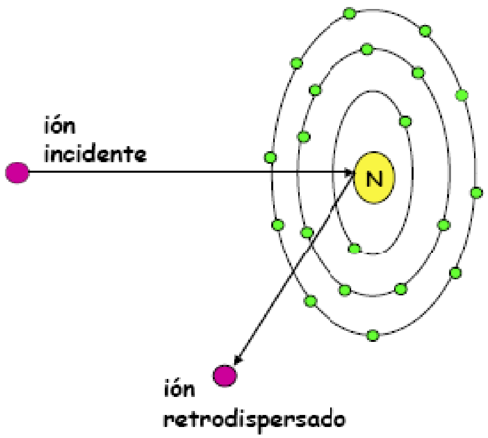
→ E_{kin} independent of I.

→ E_{kin} depends on the frequency of the light.

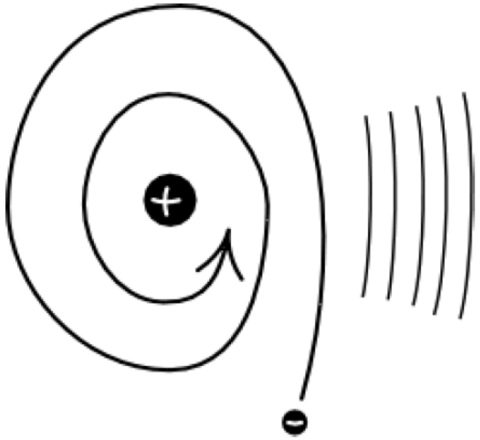
Classically one might expect it to be the reverse: the electron energies are proportional to intensity and independent of frequency.

3. The line-spectrum of atoms

1911: Ernest Rutherford's scattering of α particles towards Au-foil



→ Atomic nuclei



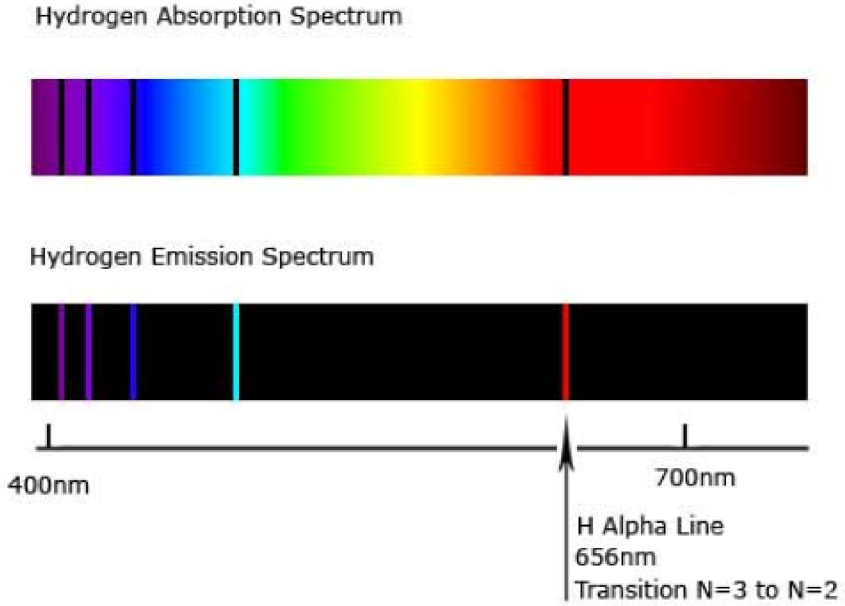
Problems:
1) what stops the electrons from falling into the nucleus?
2) Why would there be discrete enegies?

1802: Spectrum of sunlight: 4 dark lines

→ Fraunhofer lines

~1870 Atomic spectra (Rutherford, Cambridge)

→ Hα, Hβ Hγ Hδ Balmer lines

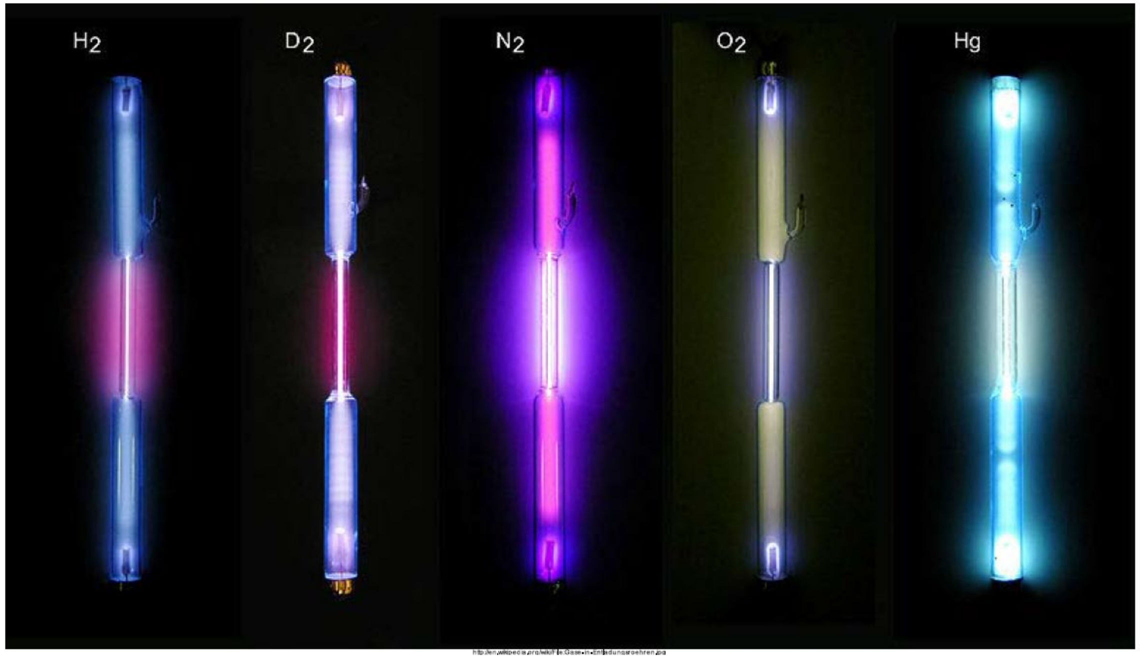


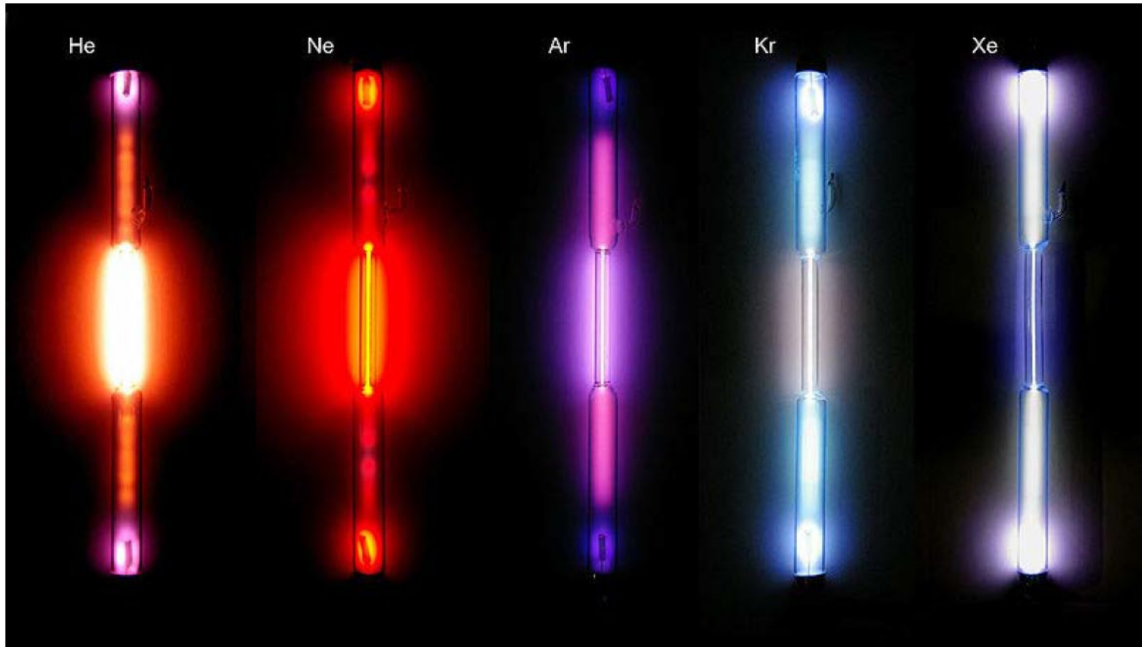
1887: Johannes Rydberg

Allowed wavelengths for Hydrogen

$$\frac{1}{\lambda} = R\left(\frac{1}{n_i^2} - \frac{1}{n_f^2}\right)$$

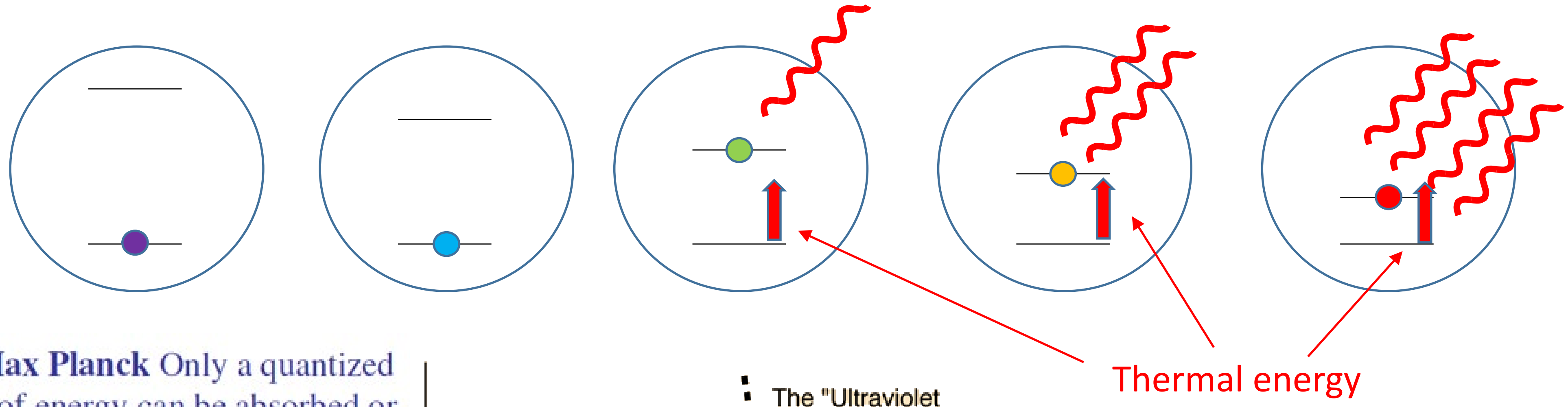
Found phenomenologically.





How to explain these puzzles?

Blackbody radiation – quantum picture



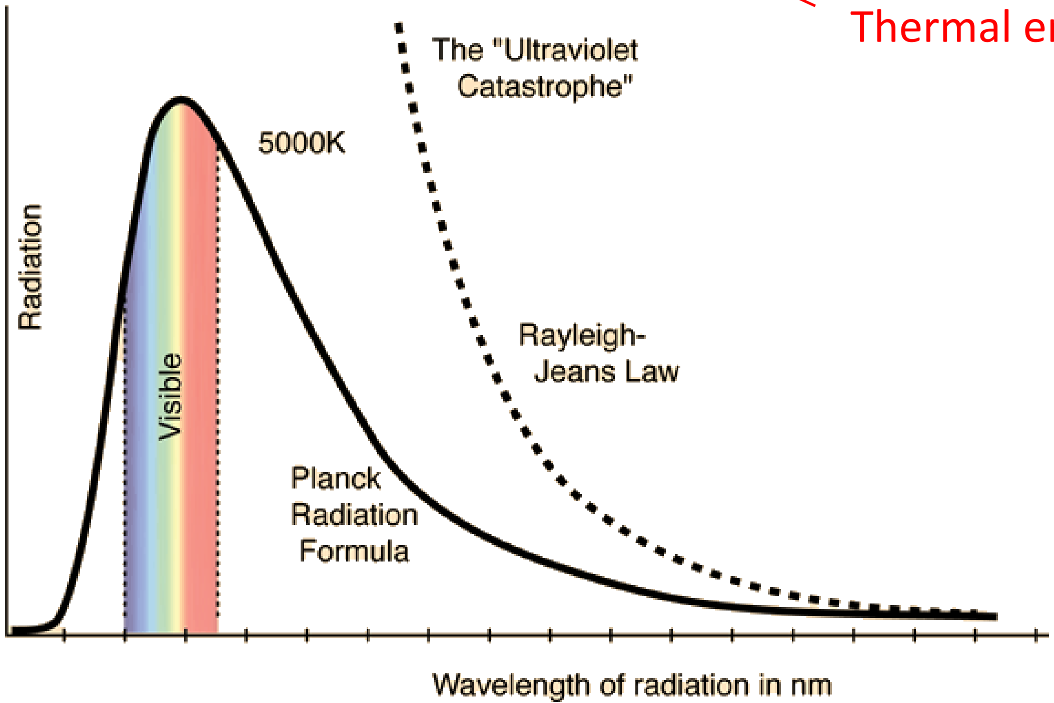
1900: **Max Planck** Only a quantized amount of energy can be absorbed or emitted.

$$E = n \cdot h\nu$$

(Nobelprize 1918)

Planck's formula for black-body radiation

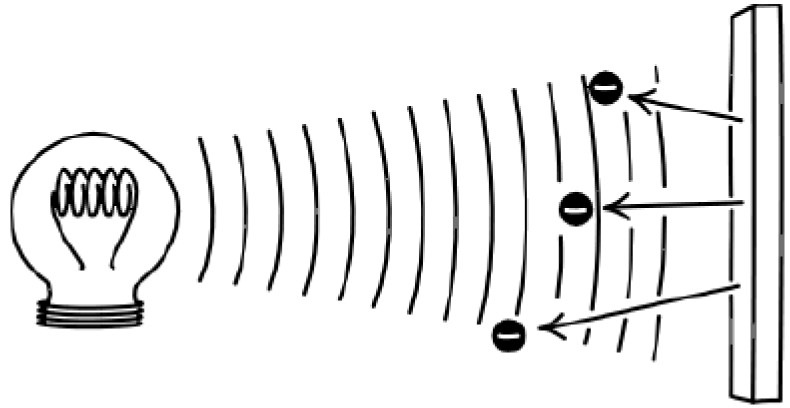
Reproduce measurements



The resonators (atom) levels are quantized! If the thermal energy is less than the unit of energy, NO light is released.

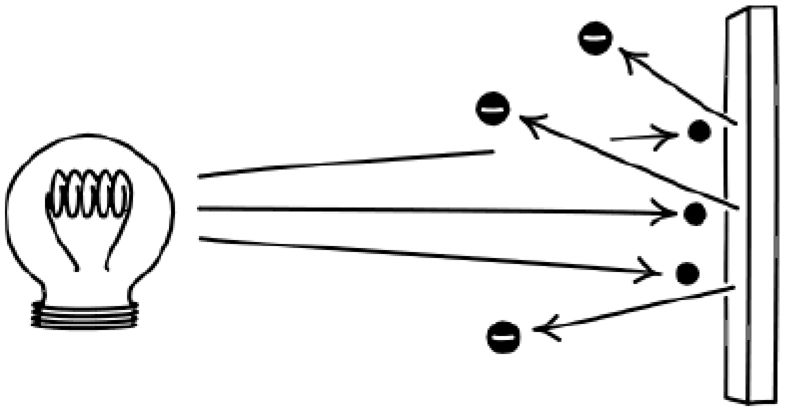
The energy levels of matter are quantized

Photoelectric effect



In a wave view, there should be a minimal amplitude of light where there would be no electrons kicked out.

Contradicts experiment!



Every photon carries an energy

$$h\nu = W_0 + E_{kin}$$

Low amplitude light just means a few photons, but they always have the energy to kick out electrons

Low frequency never can kick out electrons, individually do not have enough energy

The energy levels of light are quantized

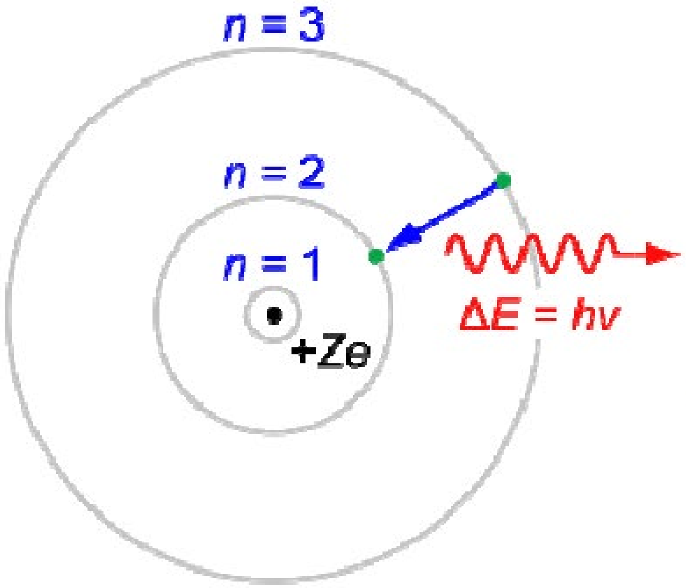
1905 A. Einstein: The energy of the light is quantized (Nobelprize 1921)

1916 The model by Einstein was confirmed experimentally by R. A. Millikan. The constant h was determined. (Nobelprize 1923)

The Bohr model

In 1913 Niels Bohr developed the Bohr model of the hydrogen atom, which could explain the observed spectrum.

(Nobel prize 1922)



$$L = mvr = n\hbar$$

$$\Rightarrow \quad E_n = \frac{E_1}{n^2}, n = 1,2,3,\ldots$$

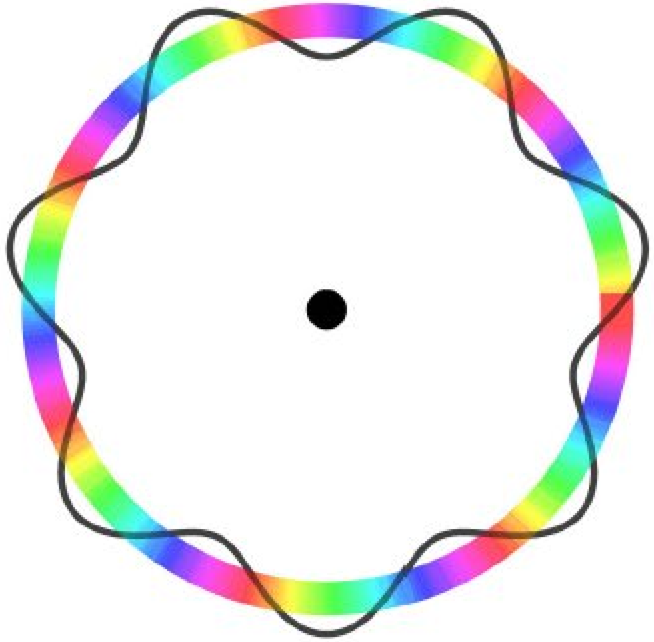
→ Why are these orbitals stable?

→ Problem to describe other atoms than H.

The energy levels of atoms are quantized

De Broglie wave length

1924 Louis deBroglie (PhD thesis) (Nobel prize 1929)



If light can have particle properties, then particles can have wave properties.

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

Einstein approved the PhD thesis!

Heisenberg's matrix algebra

Werner Heisenberg tried to understand the line spectrum of H-atom.

- Especially the Zeeman effect (what happens with the spectrum when the atom is placed in a magnetic field).

(Worked with Bohn in Copenhagen and then at Göttingen, Germany)

1925 Develops a new matrix algebra during 6 months (Nobelprize1932)

Schrödinger equation

Erwin Schrödinger, Austrian (tuberculosis)

" Quantisierung als Eigenwertproblem "

Annalen der Physik, 1926

Combined the classical wave equation with the deBroglie wave length. (Nobelprize 1933)

Article I:Time-independent Schrödinger equation for the H-atom.

Schrödinger equation

" Quantisierung als Eigenwertproblem "

Annalen der Physik, 1926

Article I:Time-independent Schrödinger equation

$$\boxed{\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x) \right)\psi(x) = E\psi(x)}$$

Article IV: Time-dependent Schrödinger equation

$$\boxed{i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x,t) \right)\Psi(x,t)}$$

(Nobelprize 1933)

Schrödinger equation

1926: Heisenberg's matrixtheory and the Schrödinger equation were found to be mathematical equivalent. (Seminar in Munich with Sommerfeld).

Copenhagen interpretation

1926: Max Born's statistical interpretation

$$\int_a^b \left|\Psi(x,t)\right|^2 dx = \begin{cases} \text{probability to find the particle} \\ \text{within } a \le x \le b \text{ at time } t \end{cases}$$

Wave function $\longrightarrow$ measurement $\xrightarrow{\text{result}}$

$\Psi = \sum_i c_i \psi_i$ $\qquad$ ψ_i

Probability to obtain a given result = $|c_i|^2$

Born's statistical interpretation

"God plays dice"

Collapse of the wave function.

Bohr, Heisenberg, Pauli

Uncertainty principle

1927: Heisenberg formulated the uncertainty principle

$$[x, \hat{p}_x] = i\hbar$$

$$\boxed{\sigma_x \sigma_y \geq \frac{\hbar}{2}}$$

Schrödinger's cat

1935: E. Schrödinger and A. Einstein proposed the gedanke experiment of the Schrödinger's cat.

Problem with the Copenhagen interpretation

$$\Psi_{cat} = c_1 \Psi_{dead} + c_2 \Psi_{alive}$$

FOWLER

PICCARD HENRIOT EHRENFEST HERZEN DE DONNER SCHROEDINGER VERSCHAFFELT PAULI HEISENBERG BRILLOUIN

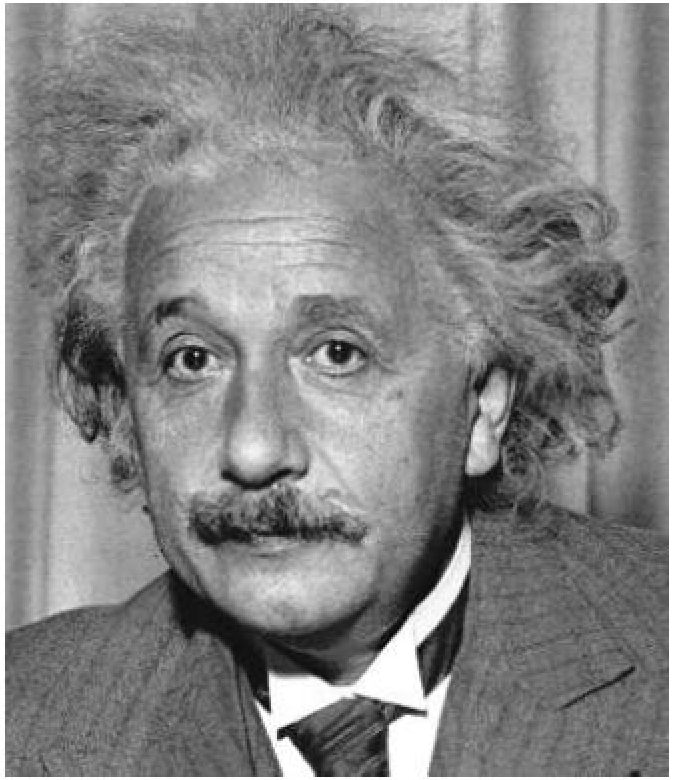
DEBYE KNUDSEN BRAGG KRANERS DIRAC COMPTON DE BROGLIE BORN BOHR

LANGMUIR PLANCK MADAME CURIE LORENTZ EINSTEIN LANGEVIN GUYE WILSON RICHARDSON

CONSEIL DE PHYSIQUE SOLVAY 1927

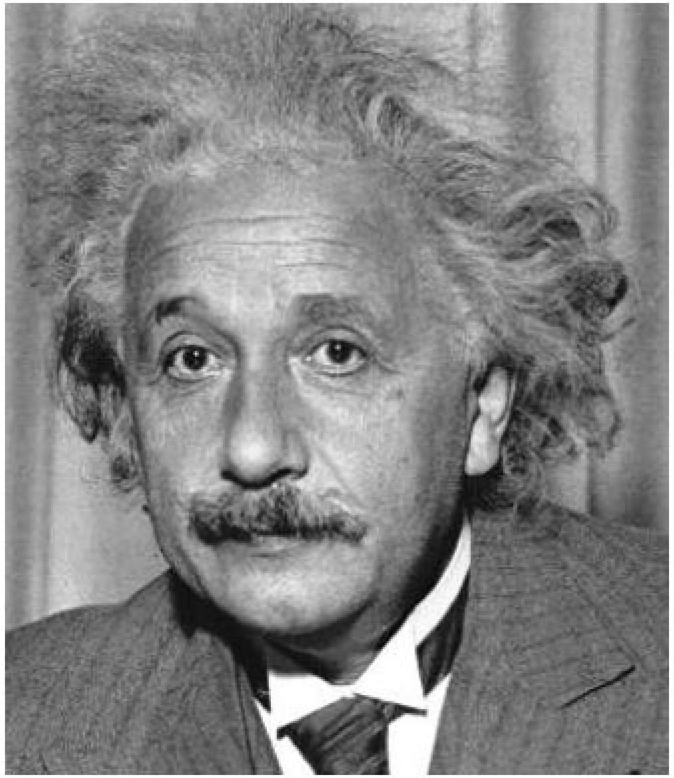
”If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet”

Niels Bohr



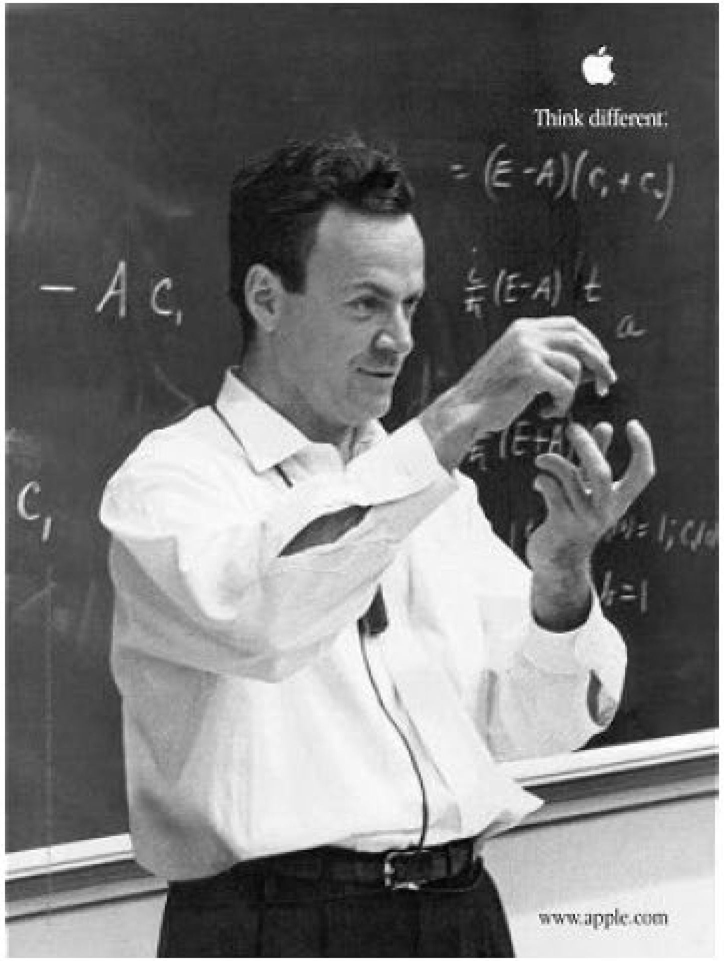
"The more success quantum theory has, the sillier it looks."

Albert Einstein



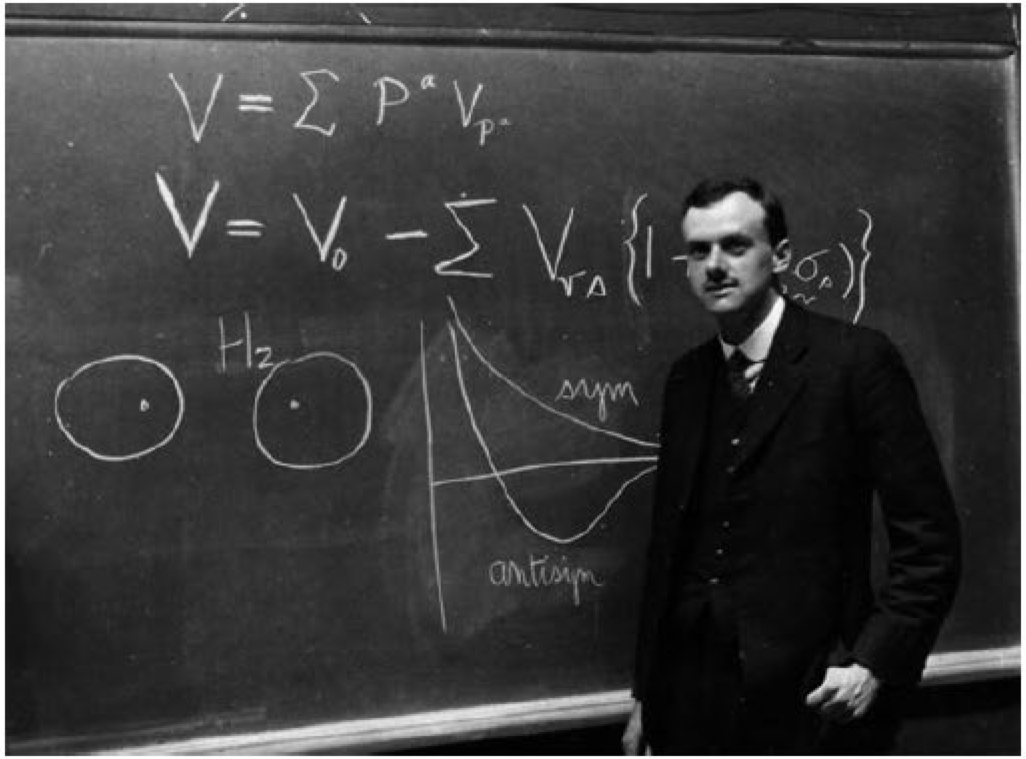
”Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing....In any case, I am convinced that He doesn't play dice.”

Albert Einstein



"Nobody understands quantum theory."

Richard Feynman



"The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble."

Paul A. M. Dirac

"I do not like quantum mechanics, and I am sorry I ever had anything to do with it."

Erwin Schrödinger