Outlines of Quantum Physics

Wave-particle duality

波粒二象性

Classical Physics

Object	Govern Laws	Phenomena
Particles	Newton's Law	Mechanics, Heat
Fields and Waves	Maxwell's Eq.	Optics, Electromagnetism

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- 黑体辐射 Blackbody radiation,
  Max Planck$_{NP1918}$: **Planck's constant**, 1900
- 光电效应 Photoelectric effect,
  Albert Einstein$_{NP1921}$: **photons**, 1905

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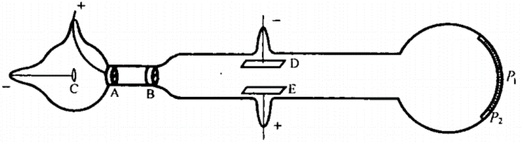
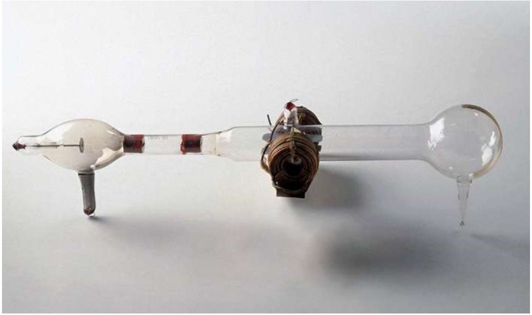
J. J. Thomson$_{NP1906}$
1856-1940





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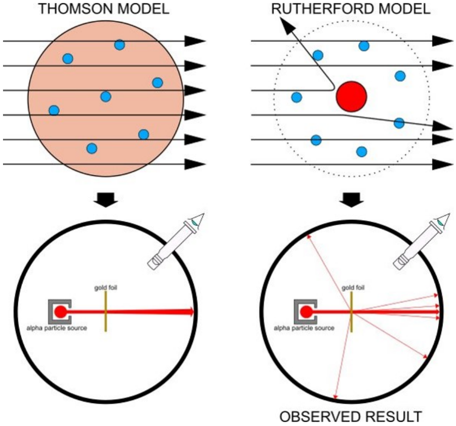
E. Rutherford$_{NC1908}$
1871-1937



First Solvay Conference, 1911

Walther Nernst, Marcel Brillouin, Ernest Solvay, Hendrik Lorentz, Emil Warburg, Jean Baptiste Perrin, Wilhelm Wien, Marie Curie, and Henri Poincaré

Robert Goldschmidt, Max Planck, Heinrich Rubens, Arnold Sommerfeld, Frederick Lindemann, Maurice de Broglie, Martin Knudsen, Friedrich Hasenörl, Georges Hostelet, Edouard Herzen, James Hopwood Jeans, Ernest Rutherford, Heike Kamerlingh Onnes, Albert Einstein, Paul Langevin

Photograph by Benjamin Couprie, 1911

Spectrum of Atomic Hydrogen

- Spectroscopy ⇔ Fingerprints of atoms & molecules ...
- Atomic Hydrogen
- Johann Jakob Balmer, 1885
  $\lambda = 364.56\frac{n^2}{n^2-4}(\text{nm})$, n =3,4,5,6
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  $\nu = \frac{1}{\lambda} = R(\frac{1}{n^2} - \frac{1}{n'^2})$
  $R = 109677\text{cm}^{-1}$

$4 \times 10^7/364.56 = 109721$
$R_H = 109677.5834...$

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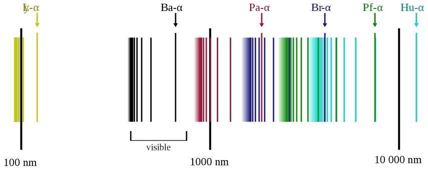

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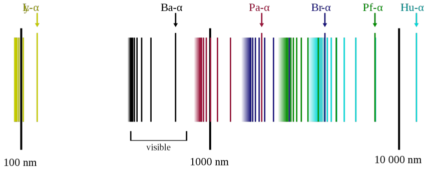

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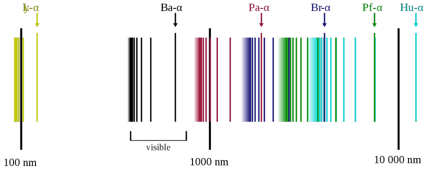

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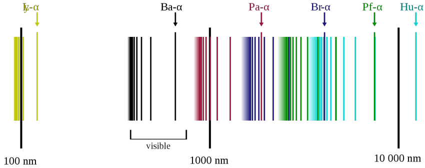

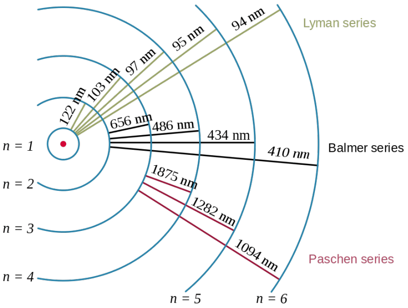

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N Bohr$_{NP1922}$ 1885-1962

Bohr's Assumption

- There are certain allowed orbits for which the electron has a fixed energy.
- The electron loses energy only when it jumps between the allowed orbits
- and the atoms emits this energy as light of a given wavelength.

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- $E = -\frac{e^2/4\pi\epsilon_0}{2r}$
- $r = a_0 n^2$, $E = -\frac{e^2/4\pi\epsilon_0}{2a_0}\frac{1}{n^2}$,
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- $\frac{m_e v^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2}$
- $E = -\frac{e^2/4\pi\epsilon_0}{2r}$
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  $hcR_\infty = \frac{(e^2/4\pi\epsilon_0)^2 m_e}{2\hbar^2}$
- $R_M = R_\infty \frac{M}{m_e+M} \simeq R_\infty(1 - \frac{m_e}{M})$

- balance between centripetal acceleration and Column attraction
- $E = \frac{1}{2}m_e v^2 - \frac{e^2/4\pi\epsilon_0}{r}$
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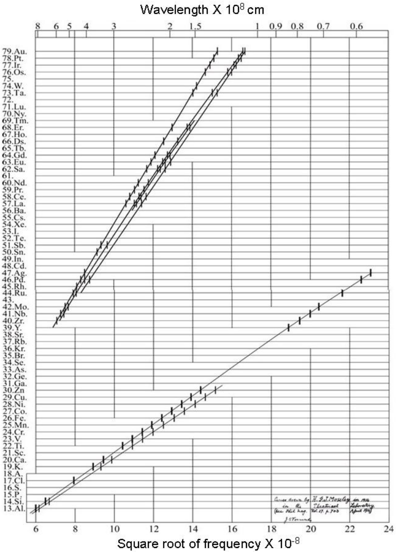
Moseley and the Atomic Number



Henry Moseley (1887-1915)

$\sqrt{f} \propto Z$

K- to L-shell transitions,

$$\frac{1}{\lambda} = R_{\infty}\left\{\frac{(Z-\sigma_K)^2}{1^2} - \frac{(Z-\sigma_L)^2}{2^2}\right\}$$

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- Cannot explain spectra of other multi-electron atoms
- Cannot explain the fine structure of H

Sommerfeld, relativistic Effects

"The integral of the momentum associated with a coordinate around one period of the motion associated with that coordinate is an integral multiple of Planck's constant. — For any physical system where the classical motion is periodic."

- Circular orbit: $m_e v \times 2\pi r = nh$
- taking $r = n^2 a_0$ and $a_0 = \frac{\hbar^2}{(e^2/4\pi\epsilon_0)m_e}$ [illegible]
- fine-structure constant $\alpha = \frac{e^2/4\pi\epsilon_0}{\hbar c} = \frac{1}{137}$
- Electrons in elliptical orbits with relativistic corrections.

$$E = -hcR[\ldots]$$ [illegible], Sommerfeld, 1916

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$$E = -hcR\left[\frac{1}{n^2} + \frac{\alpha^2}{n^4}\left(\frac{n}{k} - \frac{3}{4}\right)\right], \text{ Sommerfeld, 1916}$$

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Radiative Decay

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Radiative Decay

- An electric dipole moment $-eD$ oscillating at angular frequency ω radiates a power P,
- Total energy E of an electron in harmonic motion,
- This energy decreases at a rate equal to the power radiated,
- Classical radiative lifetime τ,
- No stable periodical orbital is allowed!

- $P = \frac{e^2 D^2 \omega^4}{12\pi\epsilon_0 c^3} = -\frac{dE}{dt}$
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- Measured lifetime of 3p level: 16.25 ns
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- Conflict between "stationary state" and Maxwell's theory

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- An electric dipole moment $-eD$ oscillating at angular frequency ω radiates a power P,
- Total energy E of an electron in harmonic motion,
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Wave-particle duality

波粒二象性

经典力学理解

波动性：可叠加性，物理量在空间的分布。
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经典理解中，二者之间有不可调和的矛盾！

彷徨，困惑的年代

“那是充满希望的春天，也是充满失望的冬天”

Bohr:“…… 与其说支持了光量子学说，倒不如说似乎对能量和动量的守恒对辐射过程的适用性提出了怀疑。”

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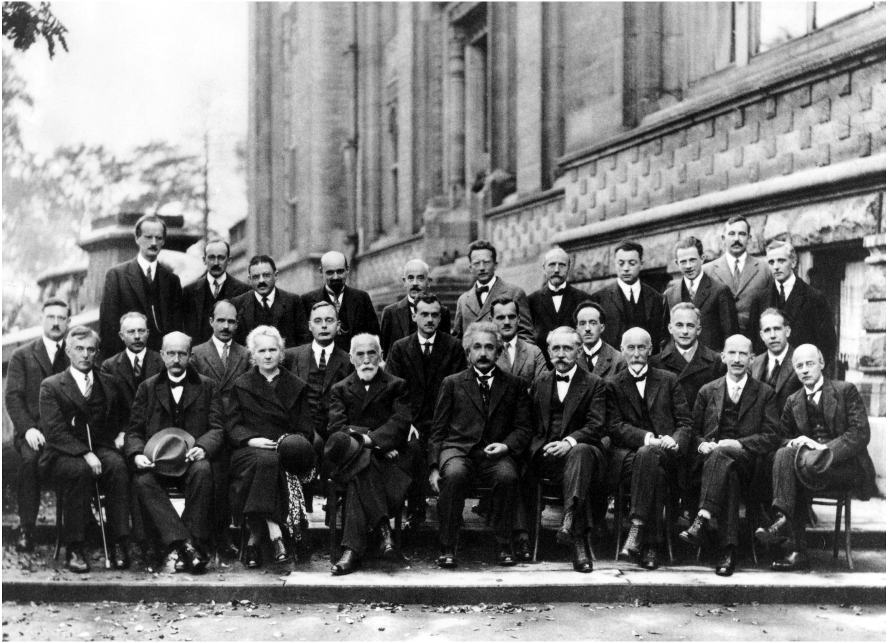

1927 Solvay Conference on Quantum Mechanics

A. Piccard, E. Henriot, P. Ehrenfest, Ed. Herzen, Th. De Donder, E. Schröinger, E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin,

P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr,

I. Langmuir, M. Planck, M. Curie, H.A. Lorentz, A. Einstein, P. Langevin, Ch. E. Guye, C.T.R. Wilson, O.W. Richardson

Photograph by Benjamin Couprie, Institut International de Physique Solvay, Brussels, Belgium

Conclusive Evidence for Wave-Particle Duality

Compton scattering

Arthur Holly Compton$_{NP1927}$, 1923
Walther Bothe$_{NP1954}$ & Hans Geiger, 1925

- $\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$
  Compton wavelength: $\frac{h}{m_e c}$=0.0243Å
- Light can behave as a stream of particles whose energy is proportional to the frequency.
- Experimental verification of momentum conservation in individual Compton scattering processes, falsifying the Bohr-Kramers-Slater (BKS) theory.

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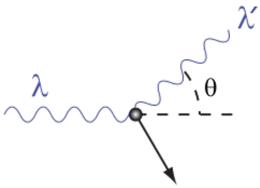

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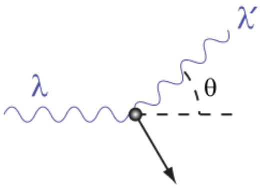

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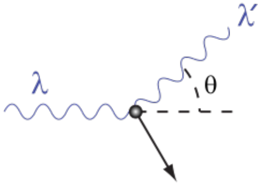

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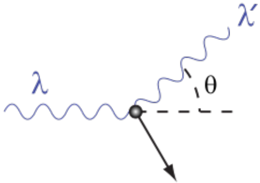

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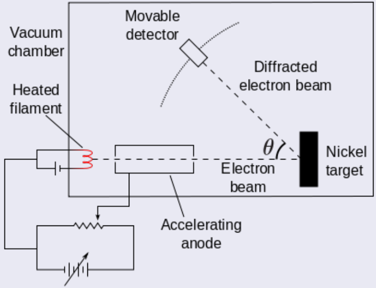
Clinton Davisson & Lester Germer, 1927



Are Electrons Waves?

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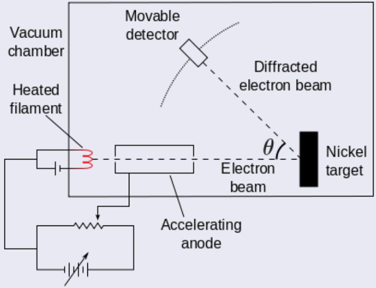

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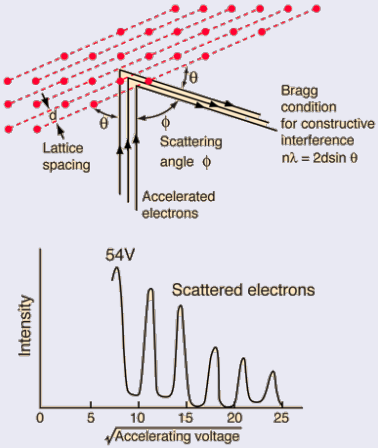

de Broglie's matter waves

Louis de Broglie$_{NP1929}$
1892-1987

物质波 Wave Structure of Matter, 1923

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

Plane wave:

$$e^{i(\vec{p}\cdot\vec{r}-Et)/\hbar}$$

Determination of the stable motion of electrons in the atom introduces integers, and up to this point the only phenomena involving integers in physics were those of interference and of normal modes of vibration. This fact suggested to me the idea that electrons too could not be considered simply as particles, but that frequency (wave properties) must be assigned to them also.

— Louis de Broglie, 1929, Nobel Prize Speech

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波粒二象性

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- 粒子性：颗粒性、不可分性（Corpuscularity），但要放弃不可测量的“轨道”

“Well, an electron is also a … wave.”

互补性原理

Complementarity Principle

— Niels Bohr

用波函数描述微观粒子

波函数是粒子状态的完全描述

几率波解释
Probability Interpretation of the Wave Function

Max Born, 1926

$\Psi(\vec{r})$,

$|\Psi(\vec{r})|^2\Delta\tau$: $\Delta\tau$ 中找到粒子的几率。

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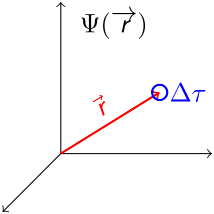

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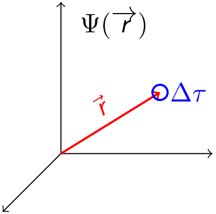

几率波解释
Probability Interpretation of the Wave Function

Max Born, 1926

$\Psi(\vec{r})$,

$|\Psi(\vec{r})|^2\Delta\tau$: $\Delta\tau$ 中找到粒子的几率。

是“预期”，而不是“本已有之”。

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波函数的统计解释对波函数的要求

1. ψ 平方可积
2. ψ 有限
3. ψ 单值

但这不是严格的要求，例外：

1. 平面波，$\Psi \sim e^{i(\vec{p}\cdot\vec{r})/\hbar}$，$\int |\psi|^2 d\tau$ 发散
2. ψ 可以有孤立奇点
3. ψ 可以有不定的相因子 $e^{i\phi}$

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态叠加原理 Principle of Superposition

$$\Psi = c_1\Psi_1 + c_2\Psi_2$$

问题

测量态 Ψ_1、Ψ_2 分别会得到测量值 a_1 和 a_2：$\Psi_1 \to a_1, \Psi_2 \to a_2$,
测量态 $\Psi = c_1\Psi_1 + c_2\Psi_2$ 会得到什么结果？$\Psi \to ?$

单光子检偏实验

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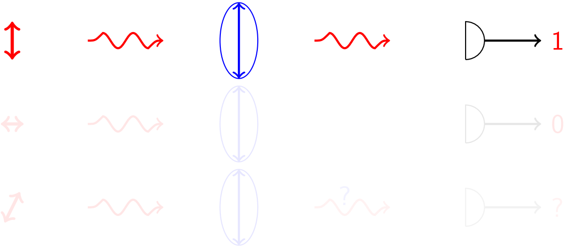

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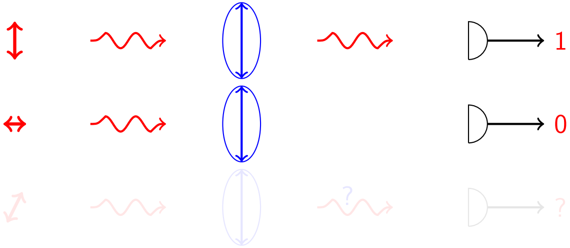

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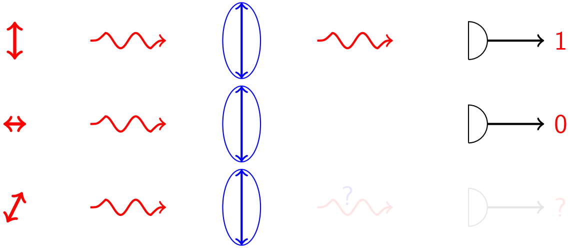

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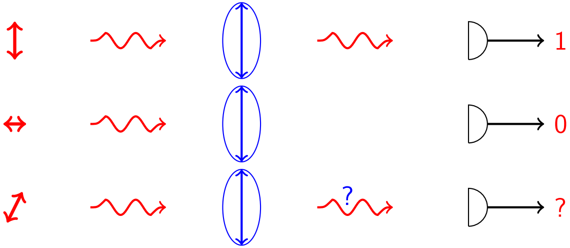

参考内容提纲

内容	参考书
氢原子光谱 Bohr 理论	【杨】§1-5 【杨】§7-10
波粒二象性	【Lv】§1.2 【杨】§12 【曾】§2.1
波函数的几率解释	【Lv】§1.6 【杨】§14 【曾】§2.2

Questions

- How do we know the energy “levels” of the hydrogen atom?
- How can a hydrogen atom be “stable”?
- What does a “transition” mean?
- The electron is also a ... “wave”?
- What is the math for a free electron?