NE290D: Special Topics in Nuclear History, Politics, and Futures
20^{th} Century Physics Part 1

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January 19, 2021 – W2L3

Agenda

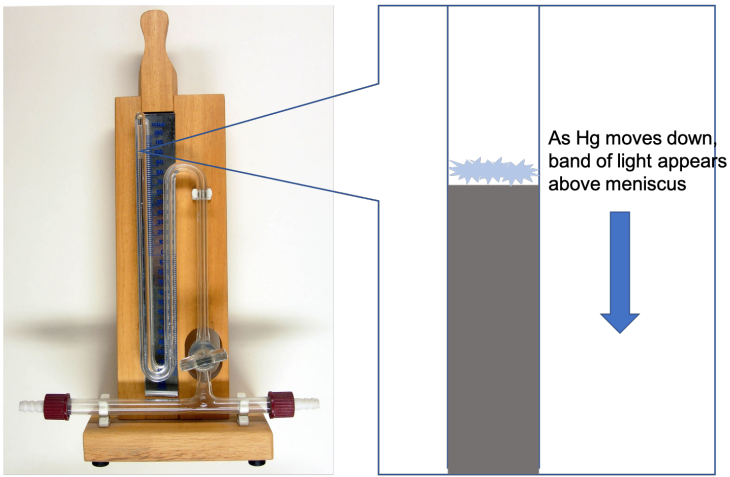
1. Setting the Stage
   1890-1899
2. A Play In 3 Parts
   1900-1910
3. Atomic Physics
   1910-1930
4. Relativity
   1910-1930
5. Quantum
   Mechanics
   1910-1930

W2L3 Learning Outcomes

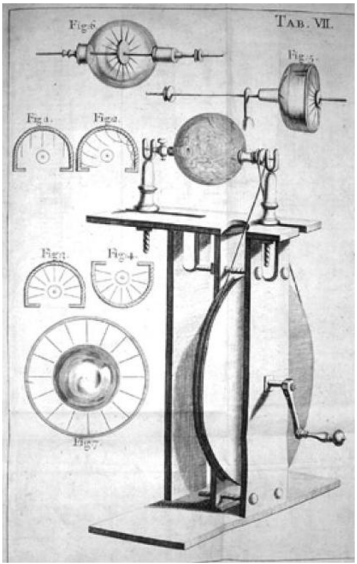
1. Recall the major historical milestones in early 20^{th} century physics and describe the experiments that led to them.
2. Organize the events on a timeline.
3. Draw connections between the developments in atomic physics, relativity, and quantum mechanics and explain how their roots in nuclear physics.
4. Weigh the importance of events and help design specific aspects of the Gather.Town project that would contribute to immersive learning environment for undergraduates.

Cathode Rays

1675: Ghostly lights in. . . . .barometers?



Setting the Stage



1719: "Influence Machine"

- "Influence machine" could produce a significant Hg discharge sufficient for the members of the Royal Society to see in daylight.
- First static generator to exceed the performance of cat fur and a glass rod

Setting the Stage

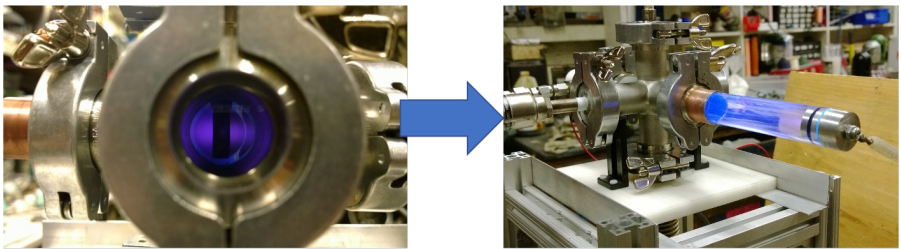
Capacititively-couple RF hydrogen plasma discharge similar to a Geissler tube (~1 Torr). Image credit: J. Hecla

1857: Geissler Tubes

- Advances in electrical apparatus made high-voltage, high-frequency sources available
- High-luminosity gas discharges could be triggered using HV power supply in tubes with $\sim$torr gas pressure

1870s: Crookes Tubes

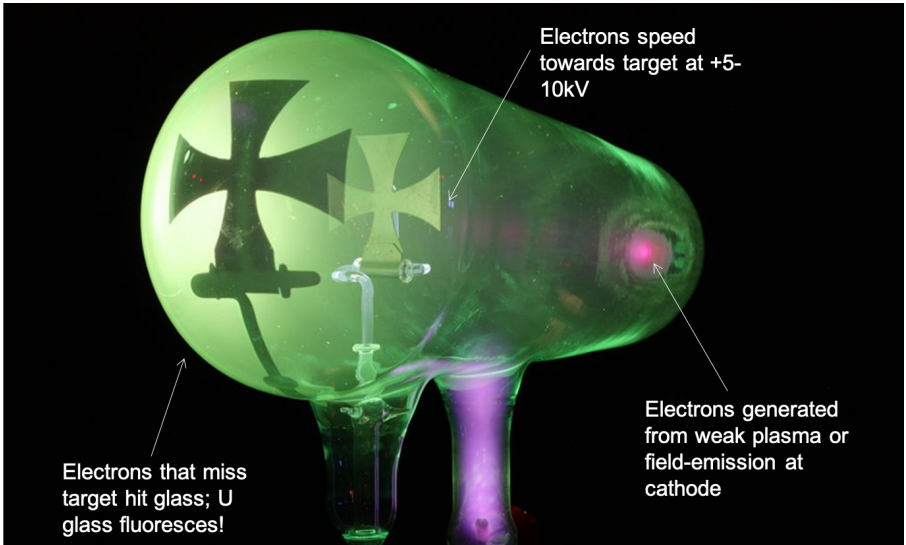
- As vacuum pump technology improved, Geissler tubes could be evacuated to the extent that the discharge changed in character
- At low pressures, no plasma, but fluorescence impacted by B-fields



Plasma discharge at ~1Torr

Spray of electrons at ~10mTorr

1880s: "Cathode rays" flew in straight lines



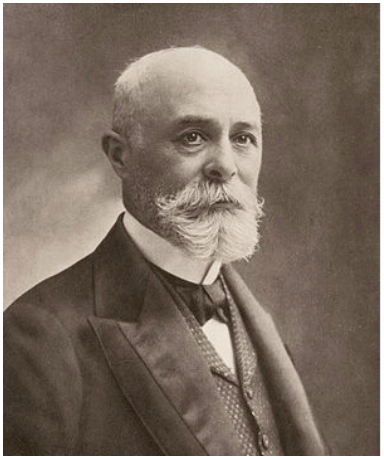
Setting the Stage

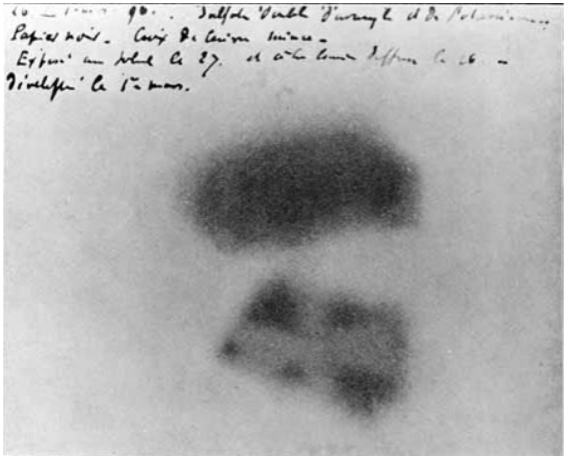
1897: Tubes generate rays which continue outside the glass

1895: X-rays Discovered by Röntgen

[1] Röntgen, Wilhelm Conrad. "On a new kind of ray, a preliminary communication." Wurzburg Physico-Médical Society on December 28 (1895).

1896: Radioactivity Discovered by Becquerel

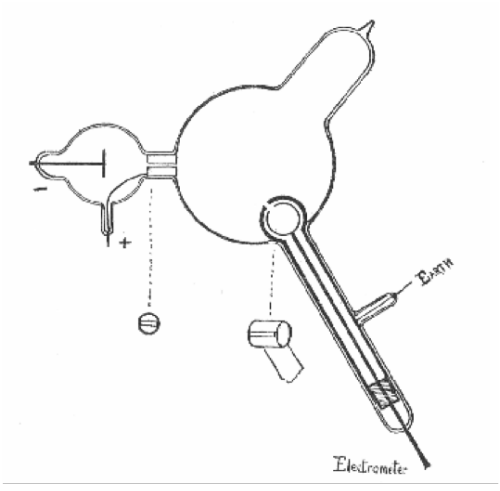




[1] Becquerel, Henri. "Sur les radiations émises par phosphorescence." Comptes rendus de 1'Academie des Sciences, Paris 122 (1896): 420-421.

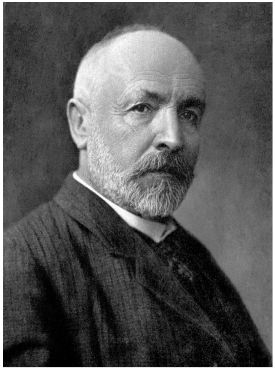
1896: Curie Begins

1897: The Electron Discovered by Thomson

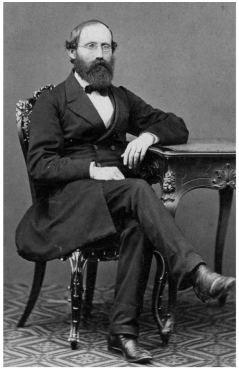


[1] Thomson, J. J. "Cathode Rays, The Electrician, vol. 39, No. 104, also published in." Proceedings of the Royal Institution. Vol. 30. 1897.

Mathematics



Cantor



Riemann

Hilbert

Poincare

1900-1910: A Play In 3 Parts

It can be argued that from 1900-1930, the stage was set for the amalgamation of nuclear physics from atomic physics, relativity, and quantum mechanics.

Atomic Physics

- Study of atoms as an isolated system of electrons and an atomic nucleus.
- Deals with the arrangement and processes of electrons surrounding the nucleus.

Relativity

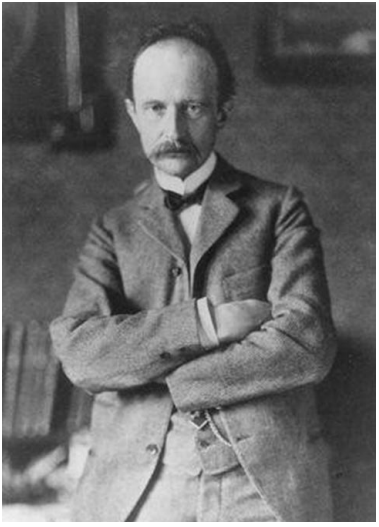
- Special relativity applies to all physical phenomena in the absence of gravity, mainly applied to speed of light.
- General relativity relates the law of gravitation to other forces such as light.

Quantum Mechanics

- Explains the aspects of nature at on the atomic and subatomic scales which classical mechanics is insufficient to describe
- Provides a set of mathematics for relating the micro to macro scales.

QM in 1900: Planck's Black-Body Radiation

- Max Karl Planck, 23 April 1858 – 4 October 1947 (aged 89)
- Sought to answer a 1959 question from Kirchoff "how does the intensity of the electromagnetic radiation emitted by a black-body depend on the frequency of the radiation and the temperature of the body?"
- Although many speculate he was interested in addressing the "ultraviolet catastrophe"



[1] Planck, Max. "On the theory of the energy distribution law of the normal spectrum." Verh. Deut. Phys. Ges 2 (1900): 237-245.

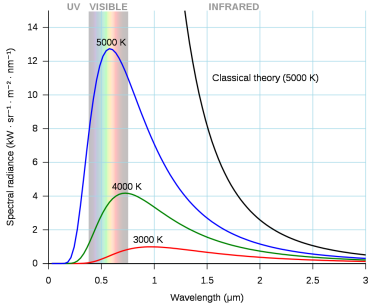
QM in 1900: Planck's Black-Body Radiation

- Derived the correct form for the intensity spectral distribution function by making some strange (for the time) assumptions.
- Electromagnetic radiation can be emitted or absorbed only in discrete packets, called quanta, of energy

$$E = h\nu = \frac{hc}{\lambda}$$

- Generally considered the birth of QM.
- Led to the spectral distriubtion function

$$B_\lambda(\lambda, T) = 2\frac{hc^2}{\lambda^5}\frac{1}{\exp(hc/(\lambda k_B T)) - 1}$$



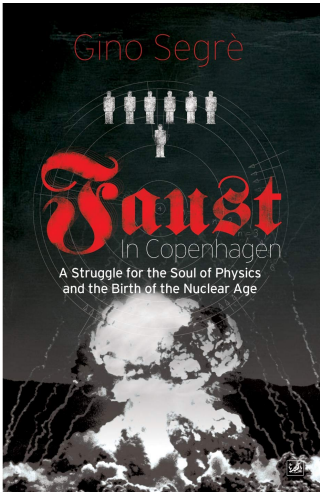
As told by Segre

Planck in FiC

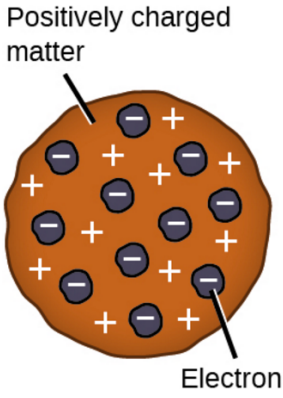
"His explanation was a radical one, causing him much anguish when he announced it. In his own words:

> *'It was an act of desperation. . . I knew the problem was fundamental and I knew the answer. I had to find a theoretical explanation at any cost, except for the inviolability of the first two laws of thermodynamics."*

By saying he knew the answer he was acknowledging that he had a formula that fit the data right away on that first evening. Deriving it from physics principles was the hard part."



AP in 1904: Thomson's Plum Pudding

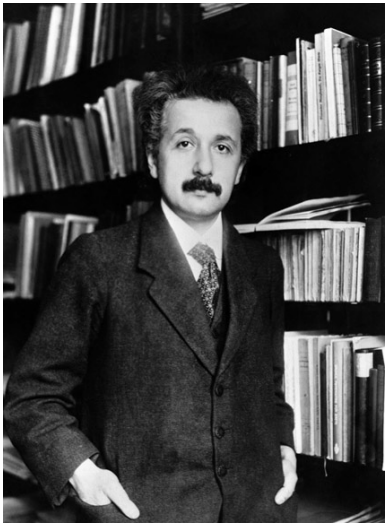


The plum pudding model depicts the electrons as negatively-charged particles embedded in a batter of positive charge. The structure of Thomson's atom is analogous to plum pudding, an English dessert.

AP and QM in 1905: Einstein's Photoelectric Effect

- The maximum kinetic energy of the electrons that were delivered this much energy before being removed from their atomic binding is

$$K_{\max} = h\nu - W = h(\nu - \nu_0)$$

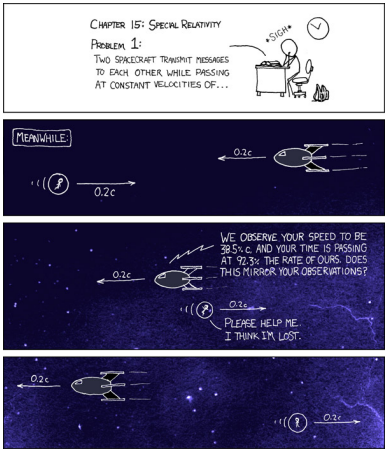


[1] Einstein, Albert. "Concerning an heuristic point of view toward the emission and transformation of light." American Journal of Physics 33.5 (1965): 367.

1900-1910: A Play In 3 Parts

R in 1905: Einstein's Special Relativity and the Mass-energy Equivalence

- A consequence of relating reference frames and Lorentz invariance
- The mass of a body approaching the speed of light becomes infinite and is limited by the speed.
- Consequences of relativity of simultaneity, time dilation, length contraction,



[1] Einstein, Albert. "On the electrodynamics of moving bodies." Annalen der physik 17.10 (1905): 891-921.

1900-1910: A Play In 3 Parts

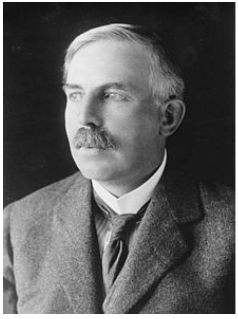
Mass-Energy from Two Sources, $E = mc^2$

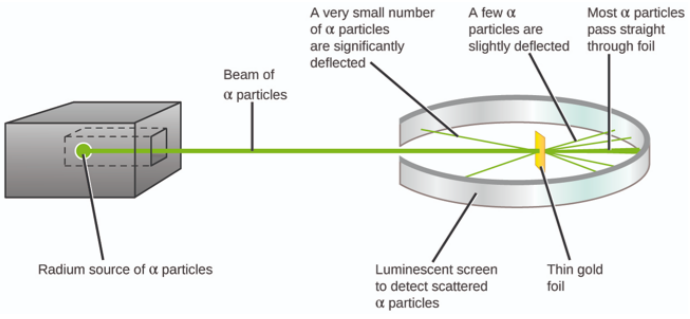
Einstein

Poincaré

[1] Einstein, Albert. "Does the inertia of a body depend upon its energy-content." Ann Phys 18 (1905): 639-641.

AP in 1911: Rutherford's Discovery of the Nucleus



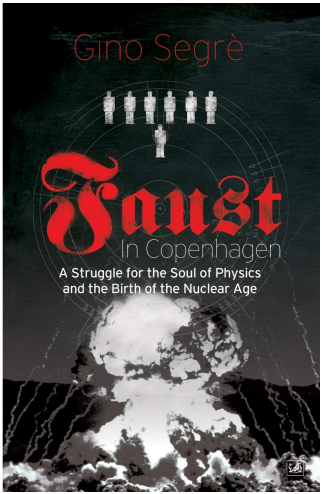


[1] Rutherford, E. "The Scattering of α and β Particles by Matter and the Structure of the Atom, Philosophical Magazine. Series 6." (1911).

As told by Segre

Planck in FiC

"Ernest Rutherford, arguably the twentieth century's greatest experimental physicist, put that topic to rest in 1911. According to him, and contrary to earlier views, the atom is mostly a great void, much like our own solar system. It holds in its core a comparatively tiny nucleus, a "fly in the cathedral" as it was sometimes referred to after Rutherford's discovery. Rutherford himself, using for comparison the great London auditorium rather than a more ecclesiastical setting, referred to the nucleus as "a gnat in Albert Hall."



1911 Solvay Conference on "The theory of radiation and quanta"

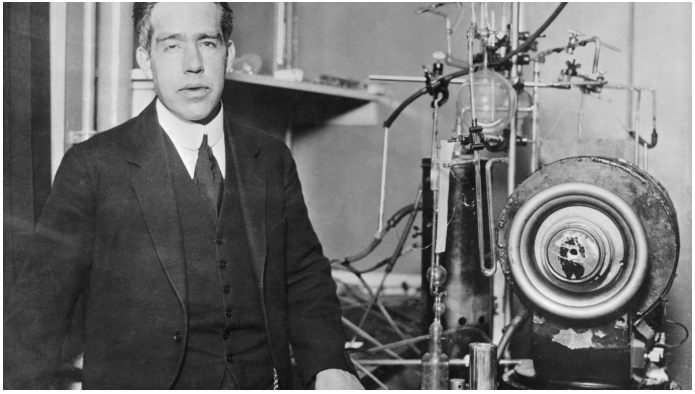
ALLIES
- M. Brillouin (FR)
- M. Curie (FR, '03, '11)
- M. de Broglie (FR)
- R. Goldschmidt (BE)
- É. Herzen (BE)
- G. Hostelet (BE)
- J. Jeans (UK)
- P. Langevin (FR)
- J. Perrin (FR, '26)
- H. Poincaré (FR)
- E. Rutherford (UK, '08)
- E. Solvay (BE)

CENTRALS
- A. Einstein (AU, '21)
- F. Hasenöhrl (AU)
- F. Lindemann (GE)
- W. Nernst (GE, '20)
- M. Planck (GE, '18)
- H. Rubens (GE)
- A. Sommerfeld (GE)
- E. Warburg (GE)
- W. Wien (GE, '11)

NEUTRALS
- M. Knudsen (DK)
- H. Lorentz (NE, '02)
- H. Onnes (NE, '13)

[1] Iaria, Alessandro, Carlo Schwarz, and Fabian Waldinger. "Frontier knowledge and scientific production: evidence from the collapse of international science." The Quarterly Journal of Economics 133.2 (2018): 927-991.

AP in 1913: Bohr's Model of the Atom

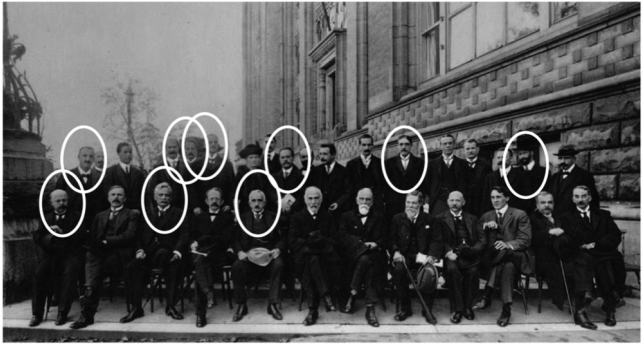


[1] Niels Bohr (1913). "On the Constitution of Atoms and Molecules, Part I" (PDF). Philosophical Magazine. 26 (151): 1–24.

[2] Niels Bohr (1913). "On the Constitution of Atoms and Molecules, Part II Systems Containing Only a Single Nucleus". Philosophical Magazine. 26 (153): 476–502.

[3] Niels Bohr (1913). "On the Constitution of Atoms and Molecules, Part III Systems containing several nuclei"

1913 Solvay Conference on "The theory of radiation and quanta"



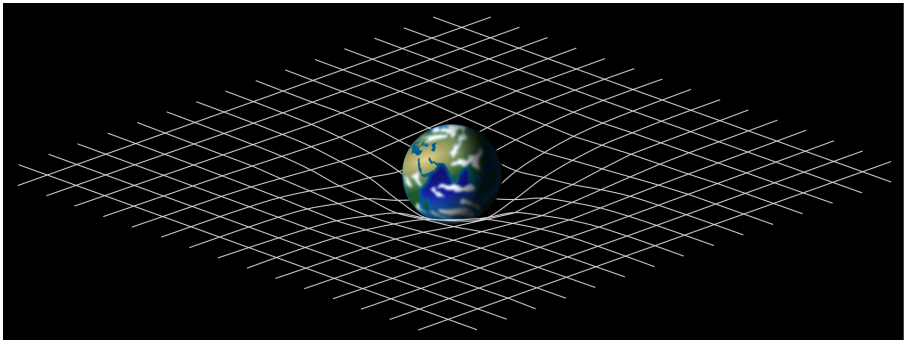
W. Barlow (UK)
W. Bragg (UK, '15)
M. Brillouin (FR)
M. Curie (FR, '03, '11)
M. de Broglie (FR)
R. Goldschmidt (BE)
L. Gouy (FR)
É. Herzen (BE)
G. Hostelet (BE)
J. Jeans (UK)
P. Langevin (FR)
W. Pope (UK)
E. Rutherford (UK, '08)
J. J. Thomson (UK, '06)
R. Wood (USA)

E. Grüneisen (GE)
F. Hasenöhrl (AU)
F. Lindemann (GE)
W. Nernst (GE, '20)
H. Rubens (GE)
A. Sommerfeld (GE)
W. Voigt (GE)
E. Warburg (GE)
W. Wien (GE, '11)

A. Einstein (SWZ, '21)
H. Lorentz (NE, '02)
M. Knudsen (DK)
H. Onnes (NE, '13)
J. Verschaffelt (NE)
M. von Laue (SWZ, '14)
P. Weiss (SWZ)

[1] Iaria, Alessandro, Carlo Schwarz, and Fabian Waldinger. "Frontier knowledge and scientific production: evidence from the collapse of international science." The Quarterly Journal of Economics 133.2 (2018): 927-991.

R in 1915: Einstein's General Relativity



$$G_{\mu\nu} = \Lambda_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

"Space-time tells matter how to move; matter tells space-time how to curve"

[1] Einstein, Albert. "The field equations of gravitation." Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.) 1915 (1915): 844-847.

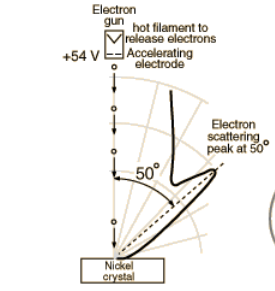
1921 Solvay Conference on "Atoms and electrons"

C. Barkla (UK, '17)
W. Bragg (UK, '15)
L. Brillouin (FR)
M. Brillouin (FR)
M. Curie (FR, '03, '11)
M. de Broglie (FR)
É. Herzen (BE)
P. Langevin (FR)
J. Larmor (UK)
A. Michelson (USA, '07)
R. Millikan (USA, '23)
J. Perrin (FR, '26)
O. Richardson (UK, '28)
E. Rutherford (UK, '08)
E. Solvay (BE)
E. van Aubel (BE)
P. Weiss (FR)

W. de Haas (NE)
P. Ehrenfest (NE)
M. Knudsen (DK)
H. Lorentz (NE, '02)
H. Onnes (NE, '13)
K. Siegbahn (SWE, '24)
J. Verschaffelt (NE)
P. Zeeman (NE, '02)

[1] Iaria, Alessandro, Carlo Schwarz, and Fabian Waldinger. "Frontier knowledge and scientific production: evidence from the collapse of international science." The Quarterly Journal of Economics 133.2 (2018): 927-991.

QM in 1923: de Broglie's Matter Waves



1924 de Broglie's hypothesis

1927 Davisson-Germer experiment

1929 Nobel Prize for de Broglie

Theory

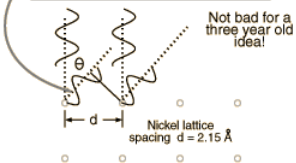
$\lambda = \frac{h}{mv} = 1.67$ Å for 54 V

Experiment

Pathlength difference

$d \sin\theta = 2.15 \sin 50^\circ = \lambda = 1.65$ Å

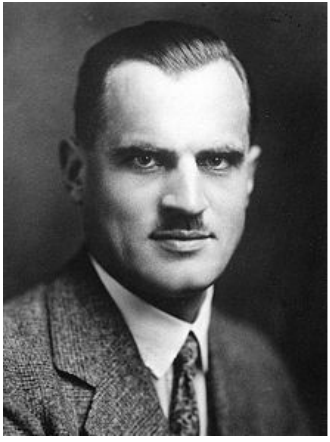
for constructive interference

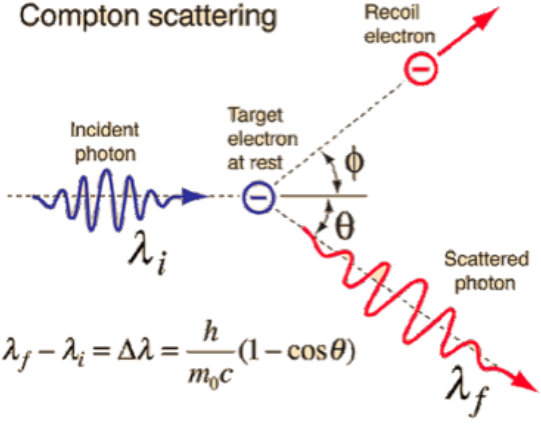


Not bad for a three year old idea!

[1] De Broglie, Louis. "Onde et quanta." Comptes rendus 177 (1923): 507.

QM in 1923: Compton Observes Photon Momentum





[1] Compton, Arthur H. "A quantum theory of the scattering of X-rays by light elements." Physical review 21.5 (1923): 483.