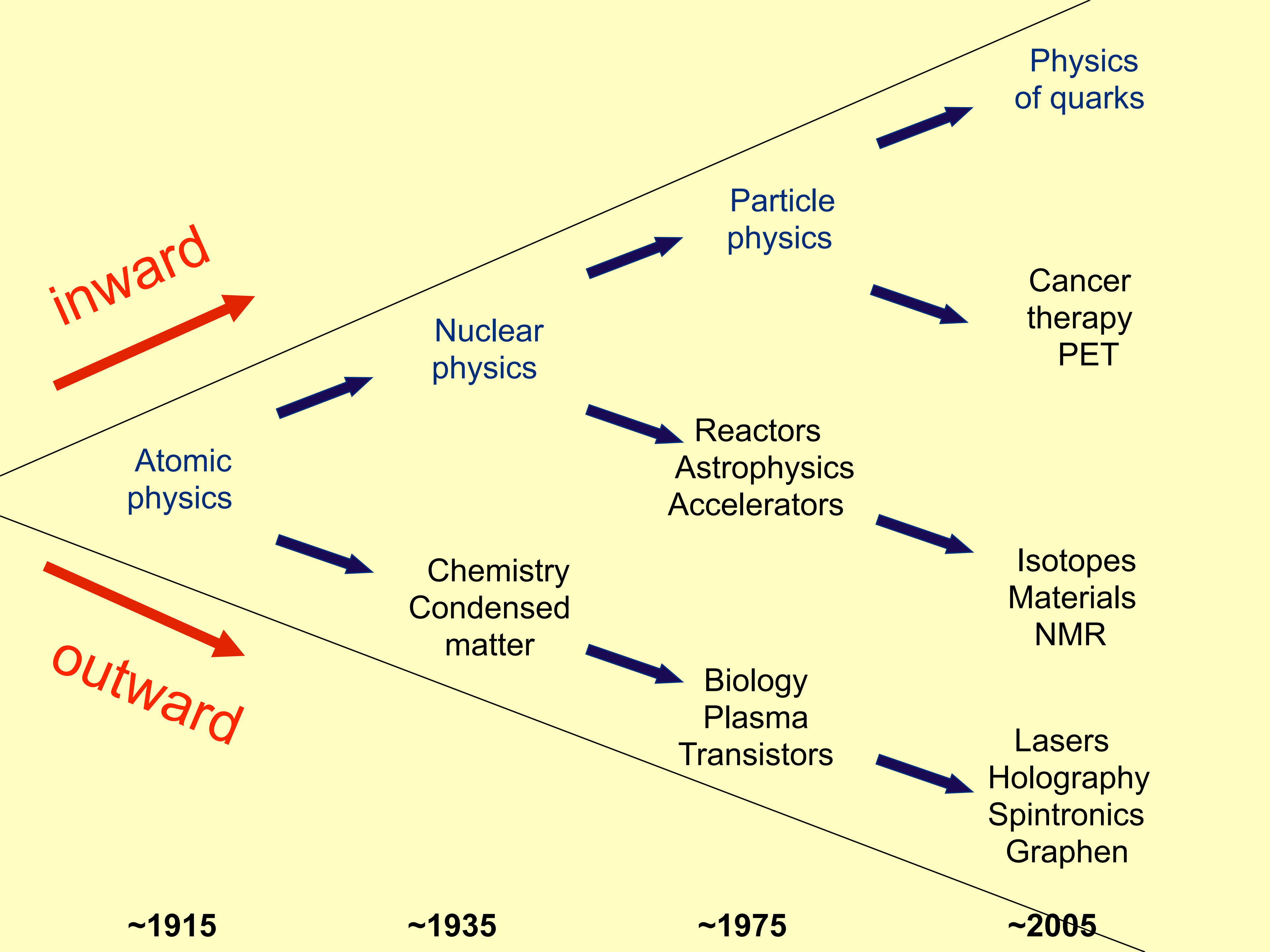
Physics of the XXth century

Part 1



inward

outward

Atomic
physics

Nuclear
physics

Chemistry
Condensed
matter

Particle
physics

Reactors
Astrophysics
Accelerators

Biology
Plasma
Transistors

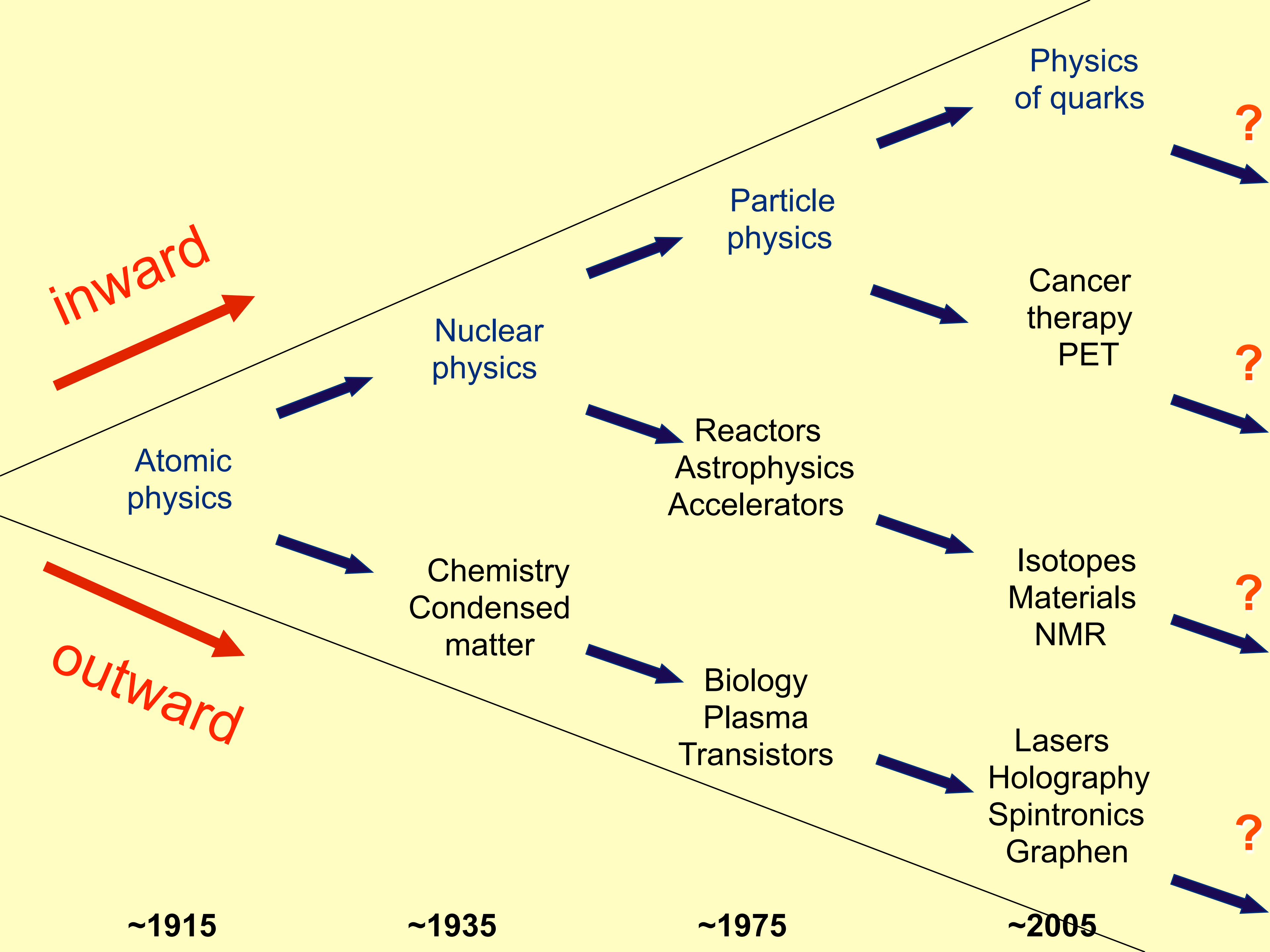
Physics
of quarks

Cancer
therapy
PET

Isotopes
Materials
NMR

Lasers
Holography
Spintronics
Graphen

~1915 **~1935** **~1975** **~2005**



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~1915 **~1935** **~1975** **~2005**

Physics of the atom
and
the path to quantum mechanics

Conclusions from experiments

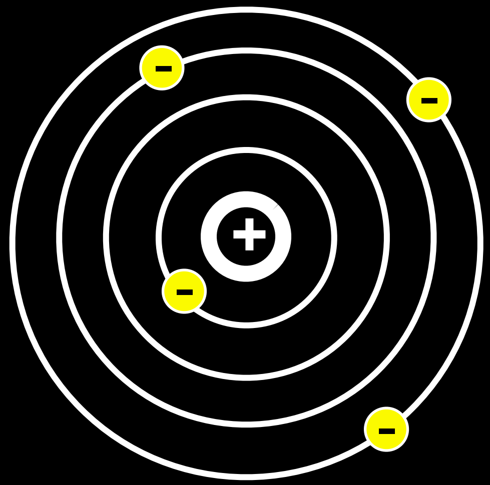
1. Matter is transparent
2. Atoms are electrically neutral
   but are formed of charged components
3. Negative particles much smaller than atoms exist
4. Atoms emit radiation of characteristic frequencies
5. Some atoms undergo transformations
   and emit energetic radiation (radioactivity)

6. Periodic system of elements

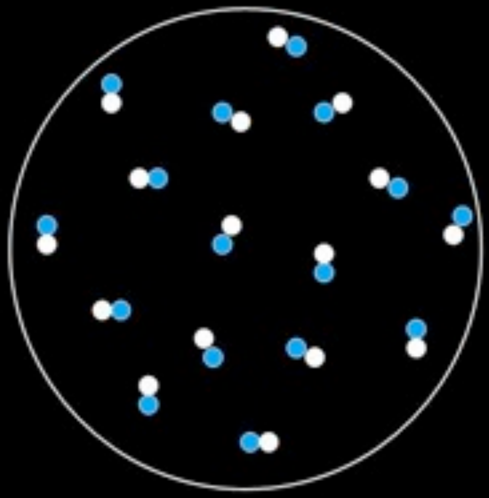
Early atomic models

1901 Jean Perrin		atoms may look like miniature planetary systems
1902 Kelvin		negative electrons in atoms form groups inside a cloud of positive charge
1903 Philipp Lenard		atoms built of ‘dynamids’ - pairs of electric charges
1904 J. J. Thomson		elaboration of qualitative Kelvin’s model ‘plum pudding model’
1904 Hantaro Nagaoka		‘Saturnian’ atom model

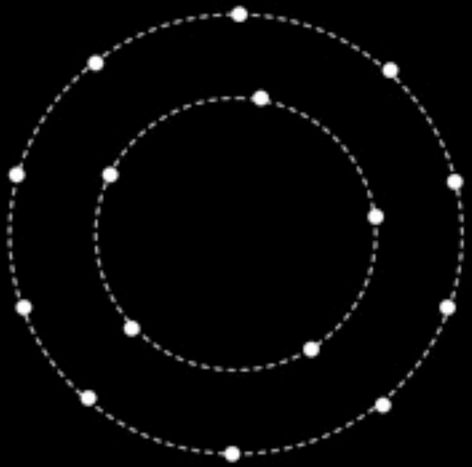
Early atomic models



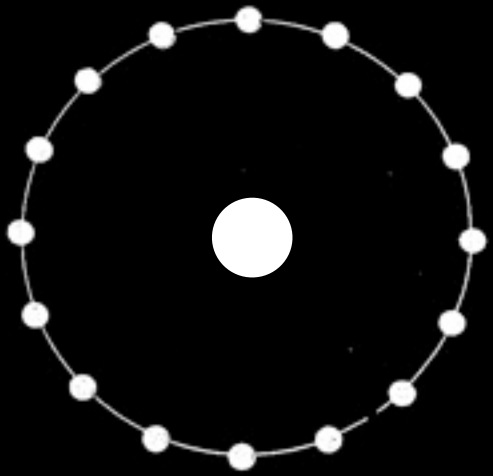
Perrin



Lenard



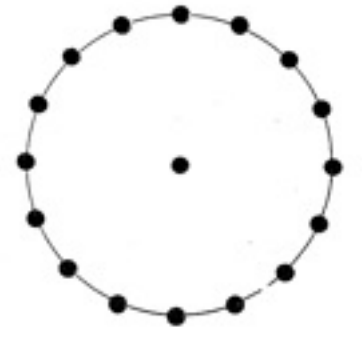
Thomson



Nagaoka

Hantaro Nagaoka

Nagaoka's atomic model of 1904

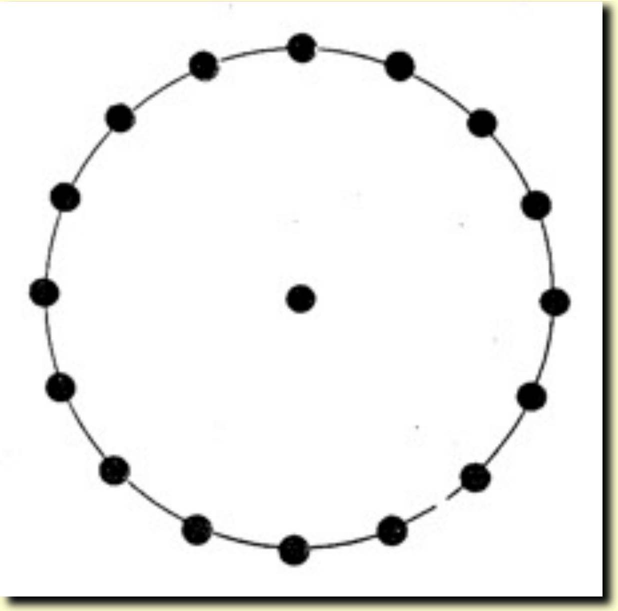


”The system, which I am going to discuss, consists of a large number of particles of equal mass arranged in a circle at equal angular intervals and repelling each other with forces inversely proportional to the square of distance; at the centre of the circle, place a particle of large mass attracting the other particles according to the same law of force. If these repelling particles be revolving with nearly the same velocity about the attracting centre, the system will generally remain stable, for small disturbances, provided the attracting force be sufficiently great... The present case will evidently be approximately realized if we replace these satellites by negative electrons and the attracting centre by a positively charged particle...”

Phil. Mag. **7**, 445 (1904); *Nature* **69**, 392 (1904)

Nagaoka's atomic model of 1904

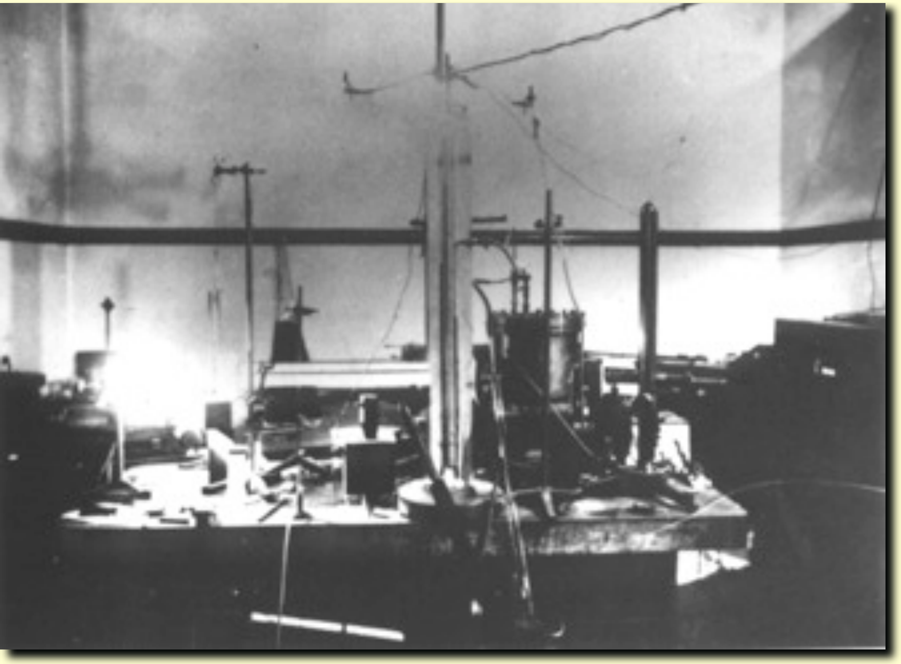
Hantaro Nagaoka

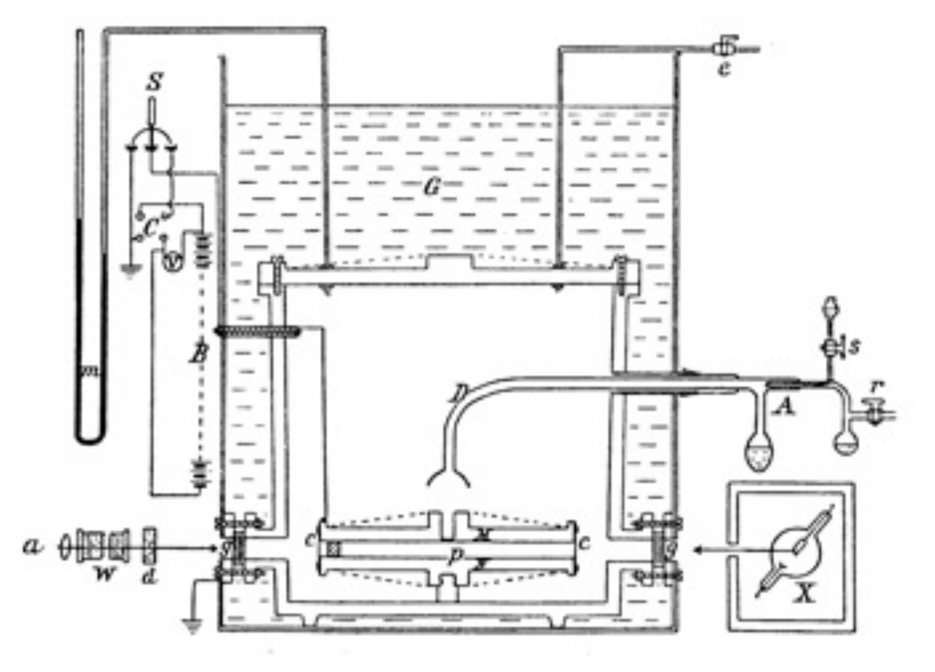


The oscillations perpendicular to the plane of the electron ring were shown to lead to a spectrum having a band-like structure and the oscillations in the plane - to a kind of line spectrum. The α- and β-rays were emitted when the electron ring and the atomic nucleus broke up because of large disturbances.

Phil. Mag. 7, 445 (1904)

Robert Millikan (1868-1953)



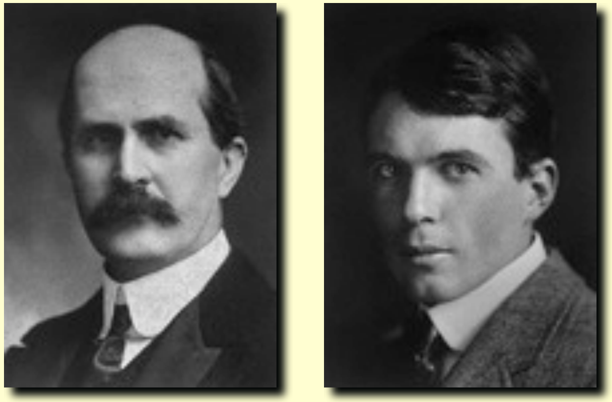


Elementary charge *e* = 4.65 x 10^{-10} electrostatic units measured by the oil-drop method [*Phil. Mag.* **19**, 209 (1910)]

Progress in understanding and using X rays

Charles Glover Barkla (1877-1944) discovered characteristic X radiation of the elements

Max von Laue (1979-1960)
together with Walter Friedrich and Paul Knipping discovered diffraction of X-rays by crystals



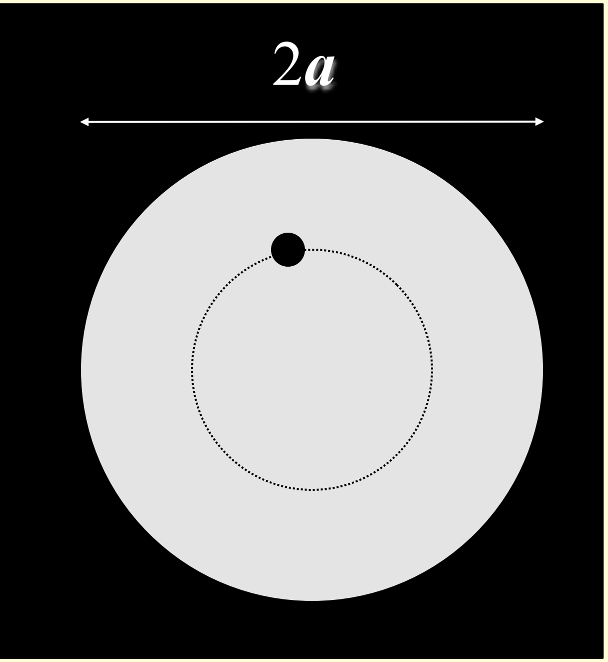
William Henry Bragg (1862-1942)
William Lawrence Bragg (1890-1971)

initiated the analysis of crystal structure by X-rays (Bragg formula for reflection)

Important events in early atomic physics

1909	Geiger & Marsden - results on α scattering by thin foils
1910	Haas - first atomic model containing Planck’s constant h
1910	Thomson - theory of scattering in the ”plum pudding” model
1911	Rutherford - nuclear atom model
1913	Van den Broek - atomic number = nuclear charge Z
1913	Van den Broek - nuclear electrons
1913	Bohr - planetary atom model
1913	Franck-Hertz experiment
1913	Geiger & Marsden - confirmation of Rutherford’s theory
1913	Moseley - frequencies of characteristic X radiation
1913	Fajans, Soddy - displacement law for radioactive decays
1913	Soddy - isotopes
1914	Chadwick - continuous spectrum of electrons in β decay
1916	Sommerfeld - extension of Bohr’s model
1921	Stern-Gerlach experiment
1922	Compton effect - scattering of X rays on free electrons
1923	de Broglie - matter waves

Arthur Haas (1910)



An electron moves on a circular orbit of radius r within a uniformly positively charged sphere of radius a. It experiences the force e^2r/a^3. The maximum energy of the electron moving in an orbit of radius a equals the limiting frequency ν^* of the Balmer spectrum multiplied by h

$$h\nu^* = e^2/a$$

If ν^* is also the frequency of the electron in this orbit, then from the equilibrium of the Coulomb attraction e^2/a^2 and the centrifugal force $4\pi^2\nu^{*2}m_e a$ an equation follows

$$h = 2\pi\,|e|\sqrt{}\,m_e a$$

which was found to be numerically satisfied

[Called a ”carnival joke” in Vienna]

John William Nicholson (1911):

1. Atoms consist of small spheres of negative electricity rotating in a ring about a smaller sphere of positive electricity, the atomic nucleus.
2. Vector sum of the accelerations of all the electrons rotating in the ring is zero.

The simplest **primary** atoms are:

Coronium	Cn	mass 0.51282	2 electrons
“Hydrogen”	H	mass 1.008	3 electrons
Nebulium	Nu	mass 1.6281	4 electrons
Protofluorine	Pf	mass 2.3615	5 electrons

All known chemical atoms are composed of these primary atoms, e.g.

Helium He = NuPf

Uranium = $8\{Nu_2(Pf\,H)_3\}4\{He_2Nu_2(Pf\,H)_3\}$

Nicholson found excellent agreement with measured values of atomic masses

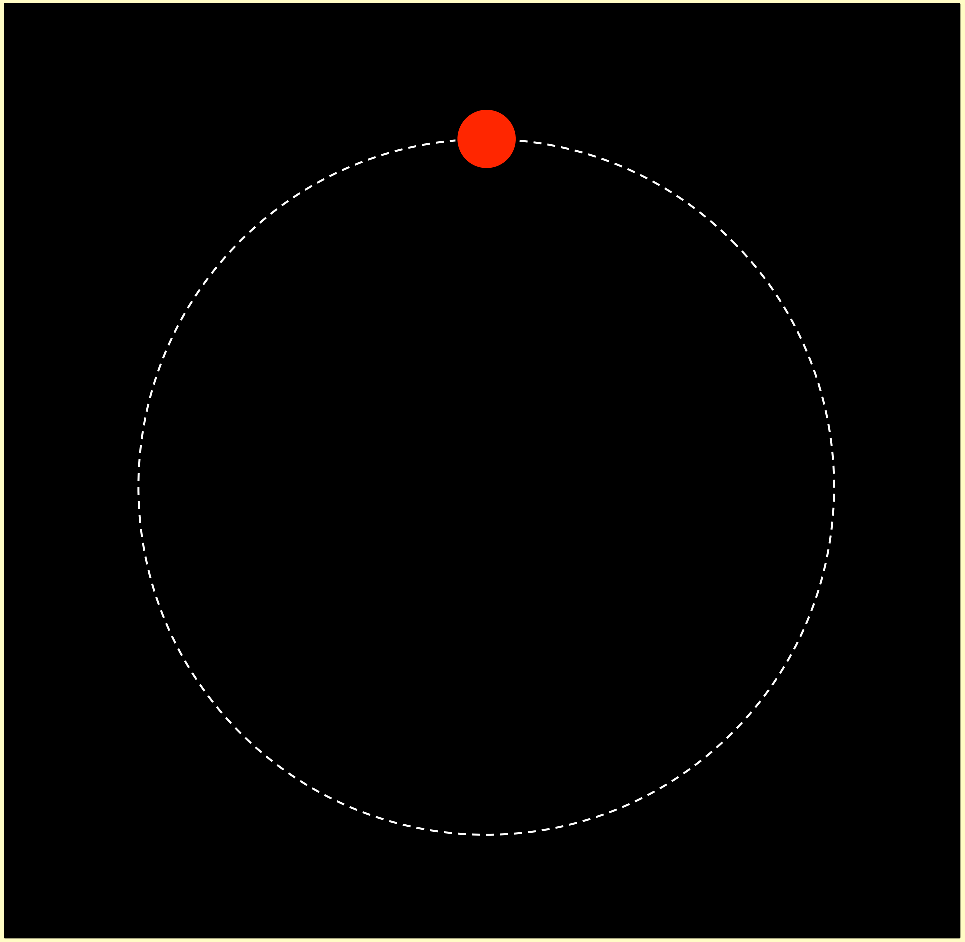
By complicated reasoning Nicholson concluded that in all primary atoms the angular momentum assumed values which were integral multiples of $h/2\pi$. For protofluorine the ratio of the potential energy of the electron ring to the rotational frequency v $(5m_e a^2\, 2\pi v^{2)}/\nu$ equals numerically $\approx 25\, h$, and this ratio corresponded to 2π times the value of the angular momentum of the electron ring.

”If, therefore, the constant *h* of Planck has, as Sommerfeld has suggested, an atomic significance, it may mean that the angular momentum of an atom can only rise or fall by discrete amounts when electrons leave or return. It is readily seen that this view presents less difficulty to the mind than the more usual interpretation, which is believed to involve an atomic constitution of the energy itself.”

Nicholson (1912)

Problems encountered by atom model builders

According to classical electrodynamics an electric charge in accelerated motion radiates energy, hence atoms lose energy and cannot be stable

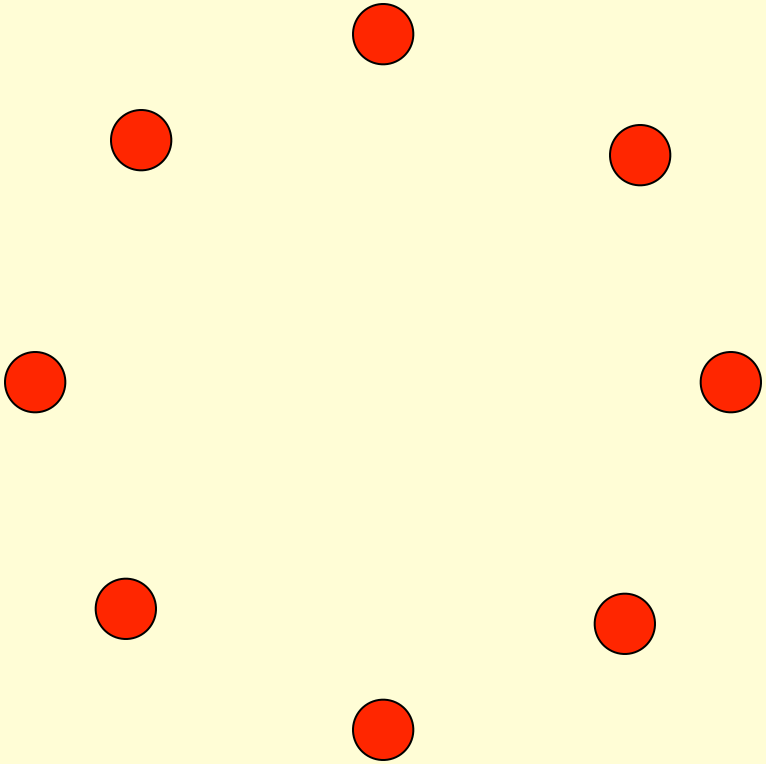


Atoms lose energy and cannot be stable

An ingenious solution proposed by J. J. Thomson:

On the Structure of the Atom: an Investigation of the Stability and Periods of Oscillation of a Number of Corpuscules arranged at equal Intervals around the Circumference of a Circle,
Phil. Mag. **7**, 237-265 (1904)

Because of destructive interference the
intensity of radiation by electric charges
moving as a ring is reduced
by many orders of magnitude;
hence, atoms can be quasi-stable



Attenuation of radiation for rings of electrons circulating with $v = 0.01\,c$

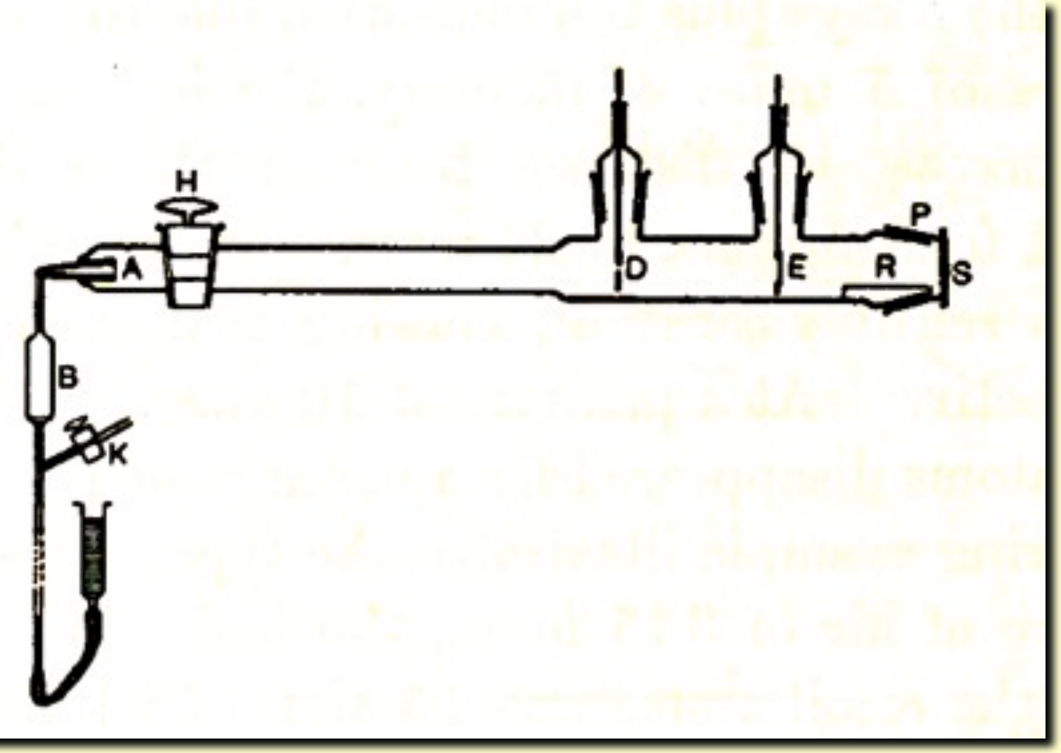
4	$1.7\ 10^{-10}$
5	$5.6\ 10^{-13}$
6	$1.6\ 10^{-17}$

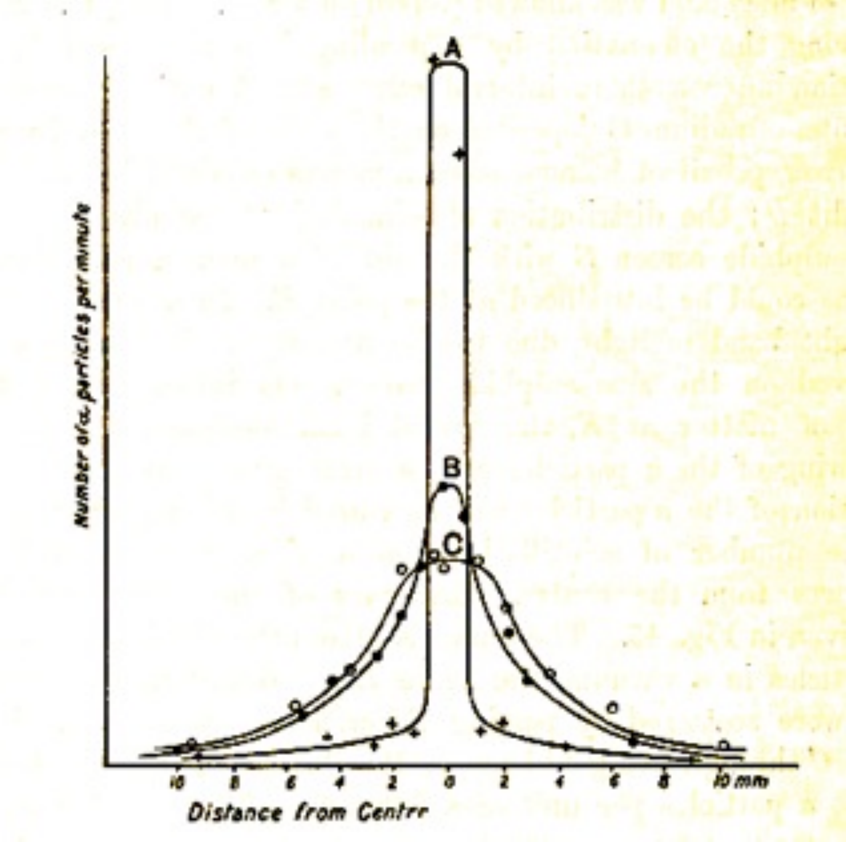
In 1912 Rutherford considered

”...the instability of the central nucleus and the instability of the electronic distribution. The former type of instability leads to the expulsion of an α particle, the latter to the appearance of β and γ-rays...”

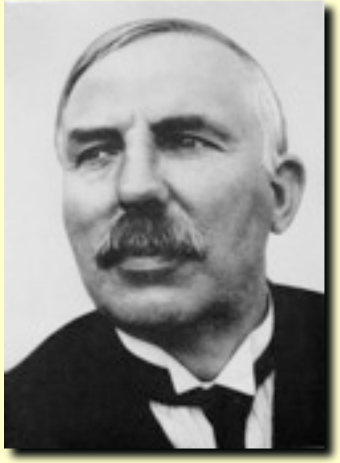
Phil. Mag. **24**, 453 (August 1912)

H. Geiger – On the Scattering of the α-Particles by Matter, *Proc. Roy. Soc*. **81**, 174 (1908)



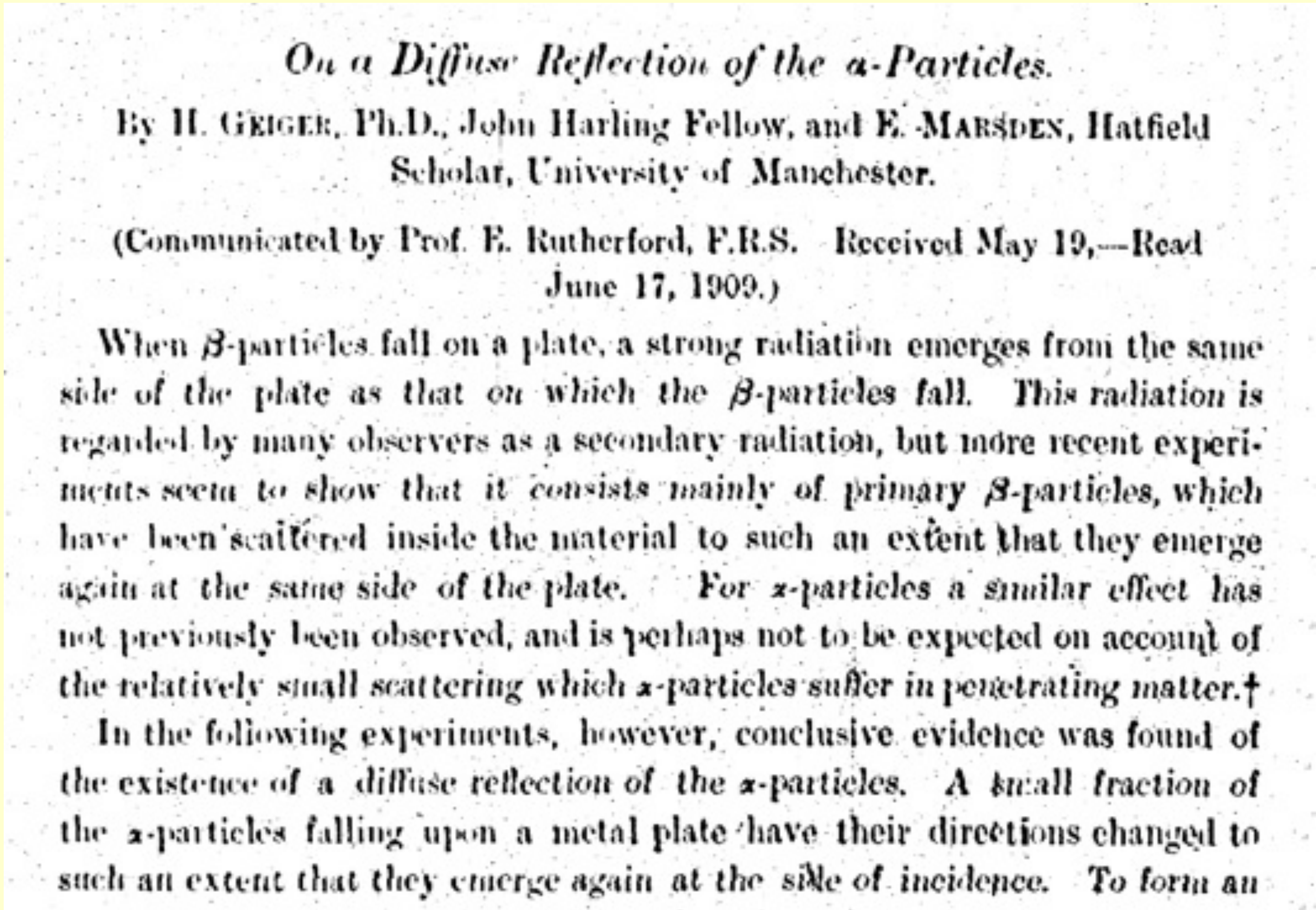


A – vacuum
B – one gold foil
C – two gold foils



”One day Geiger came to me and said: 'Don't you think that young Marsden whom I am training in radioactive methods ought to begin a small research?' Now I had thought so too, so I said, 'Why not let him see if any alpha-particles can be scattered through a large angle?' The result was quite extraordinary.”

Rutherford, Lecture in Cambridge (1936)



On a Diffuse Reflection of the α-Particles.

By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.

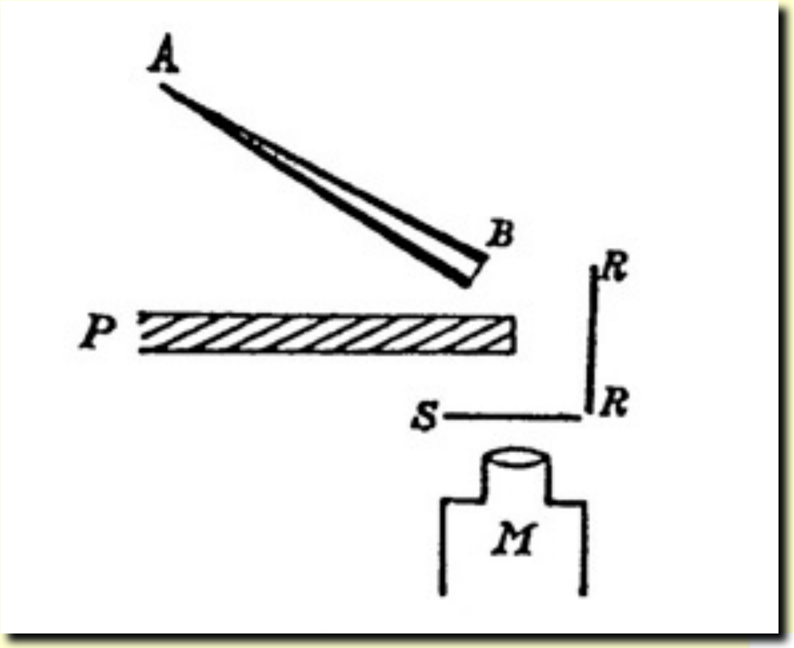
(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read June 17, 1909.)

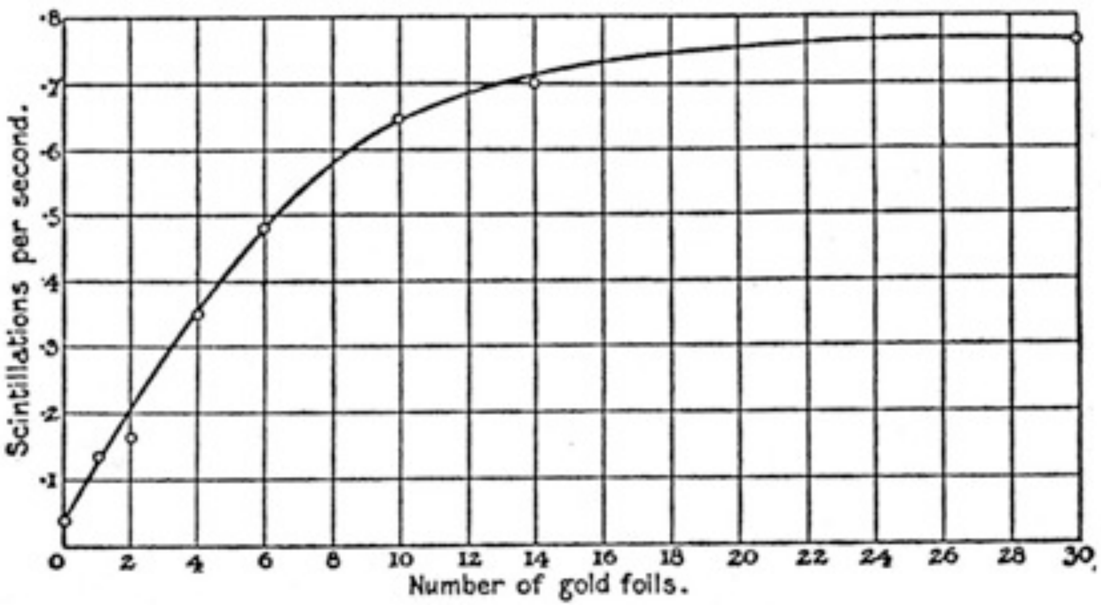
When β-particles fall on a plate, a strong radiation emerges from the same side of the plate as that on which the β-particles fall. This radiation is regarded by many observers as a secondary radiation, but more recent experiments seem to show that it consists mainly of primary β-particles, which have been scattered inside the material to such an extent that they emerge again at the same side of the plate. For α-particles a similar effect has not previously been observed, and is perhaps not to be expected on account of the relatively small scattering which α-particles suffer in penetrating matter.†

In the following experiments, however, conclusive evidence was found of the existence of a diffuse reflection of the α-particles. A small fraction of the α-particles falling upon a metal plate have their directions changed to such an extent that they emerge again at the side of incidence. To form an

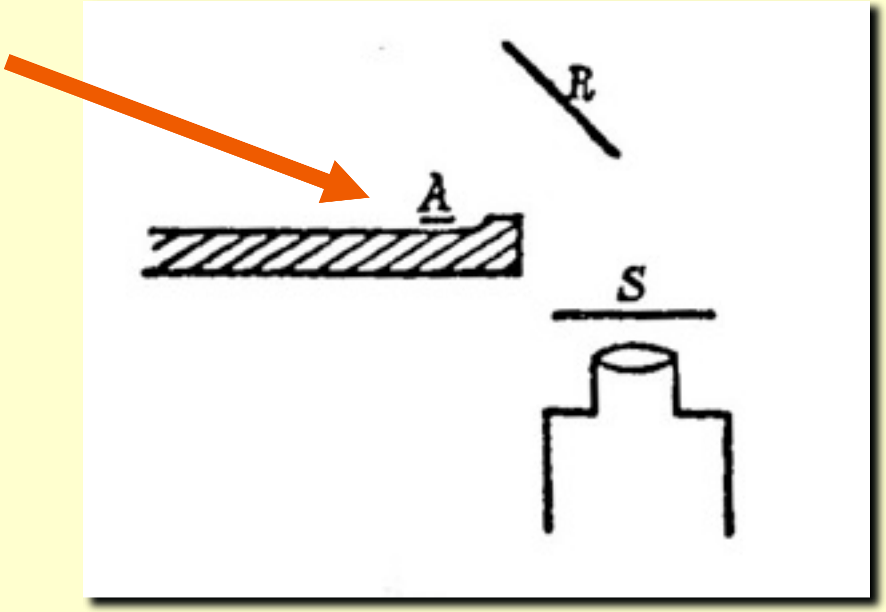
Proc. Roy. Soc. **82**, 495 (1909)

Geiger-Marsden experiment (1909)



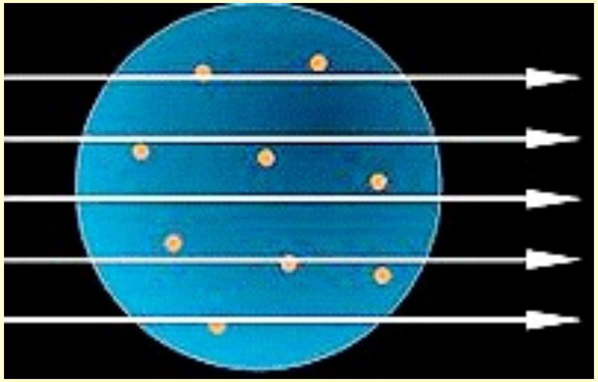


Geiger-Marsden experiment (1909)

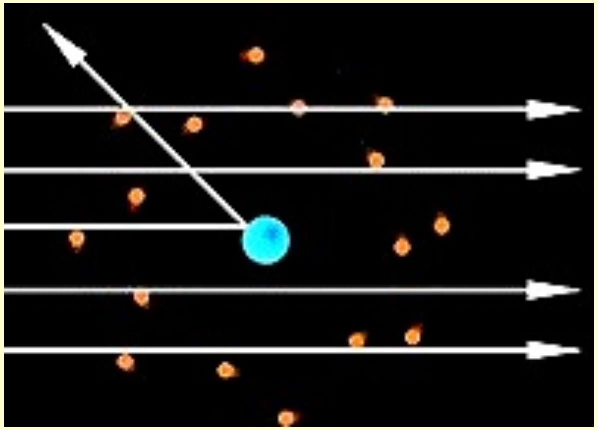


Conclusion: one in about 8000 incident alpha particles was reflected at a large angle

"It was as though you had fired
a fifteen-inch shell at a piece of tissue
paper and it had bounced back and hit you."



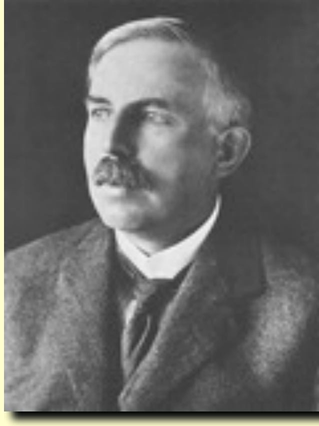
In the ”plum-pudding” model of J. J. Thomson scattering of alpha-particles occurs predominantly at very small angles



Scattering of alpha-particles at large angles gives evidence of the large central charge, the atomic nucleus (Rutherford model)

“The question of the stability of the atom proposed need not be considered at this stage, for this will obviously depend upon the minute structure of the atom, and on the motion of the constituent charged parts.”

The Scattering of α and β Particles by Matter and the Structure of the Atom,
Phil. Mag. **21**, 669 (1911)



"I am beginning to think that the central core is **negatively charged**, for otherwise the law of absorption for beta rays would be very different from that observed..."

Letter to William Henry Bragg, February 9, 1911

"The scattering of the electrified particles is considered for a type of atom which consists of a central electric charge concentrated at a point and surrounded by a uniform spherical distribution of **opposite electricity** equal in amount."

Abstract of a paper read before the Society on March 7, 1911.
Proc. Manchester Literary and Philosophical Society, IV, 55, 18.

"Consider an atom which contains a charge ± Ne at its centre surrounded by a sphere of electrification containing ∓ Ne supposed uniformly distributed throughout a sphere of radius R... It will be shown that the main deductions from the theory are independent of whether the central charge is supposed to be positive or negative. For convenience, the sign will be assumed to be positive... It has not so far been found possible to obtain definite evidence to determine whether it be positive or negative..."

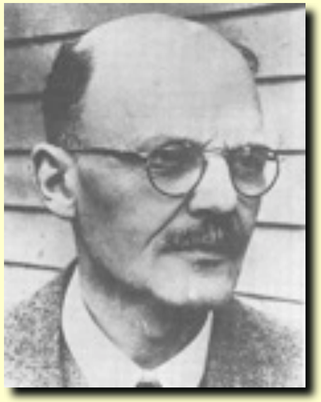
Phil. Mag. 21, 669 (May 1911)

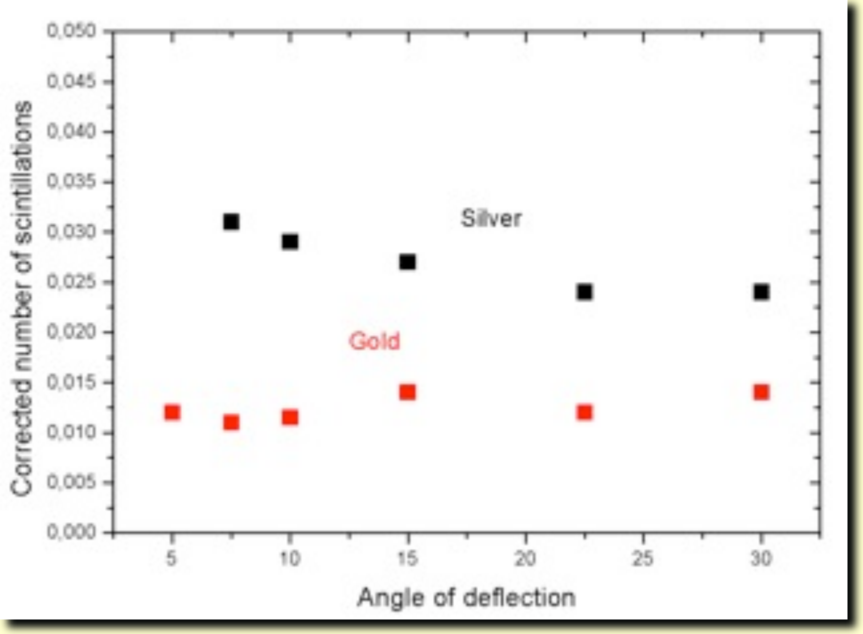
"...I supposed that the atom consisted of a **positively charged** nucleus of small dimensions in which practically all the mass of the atom was concentrated. The nucleus was supposed to be surrounded by a distribution of electrons to make the atom electrically neutral, and extending to distances from the nucleus comparable with the ordinary accepted radius of the atom."

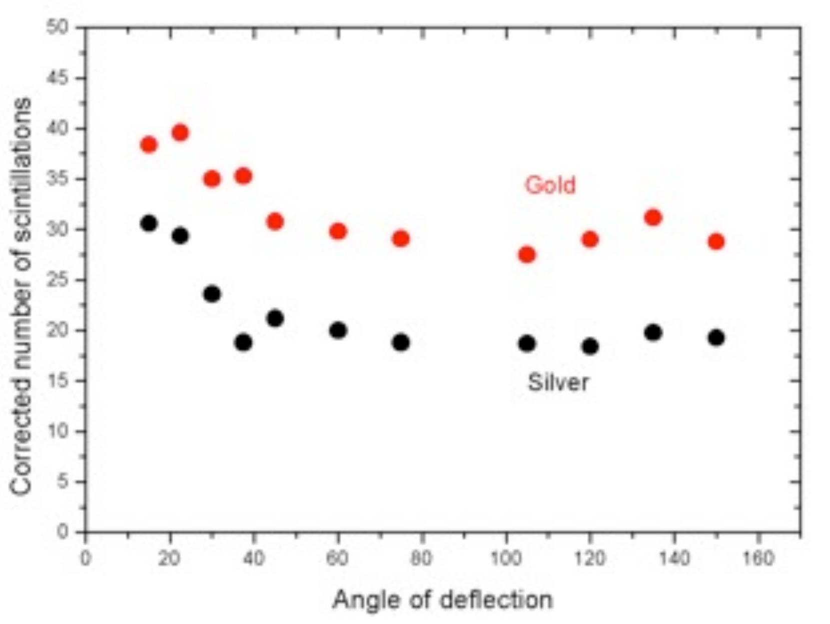
Phil. Mag. 27, 488 (March 1914)

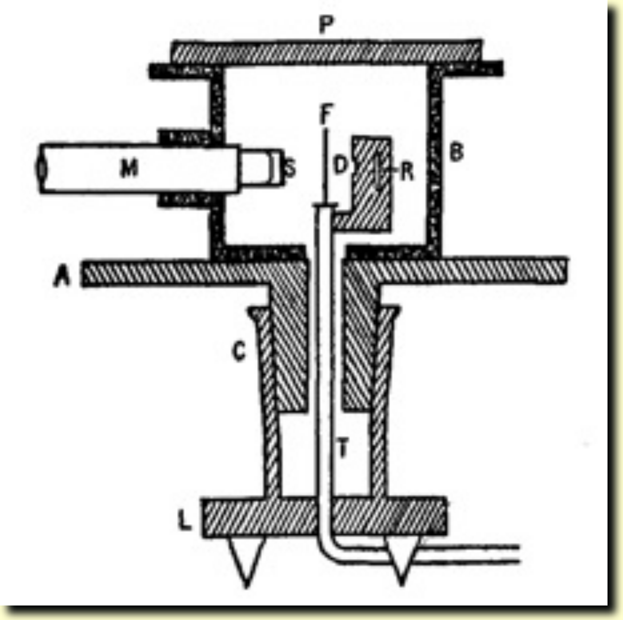
”Professor Rutherford has recently developed a theory to account for the scattering of α particles through these large angles, the assumption being that the deflexions are the result of an intimate encounter of an α particle with a single atom of the matter traversed. In this theory an atom is supposed to consist of a strong positive or negative central charge concentrated within a sphere of less than 3 x 10^{-12} cm radius, and surrounded by electricity of the opposite sign distributed throughout the remainder of the atom of about 10^{-8} cm radius.”

Hans Geiger and Ernest Marsden,
Phil. Mag. **25**, 604 (1913)





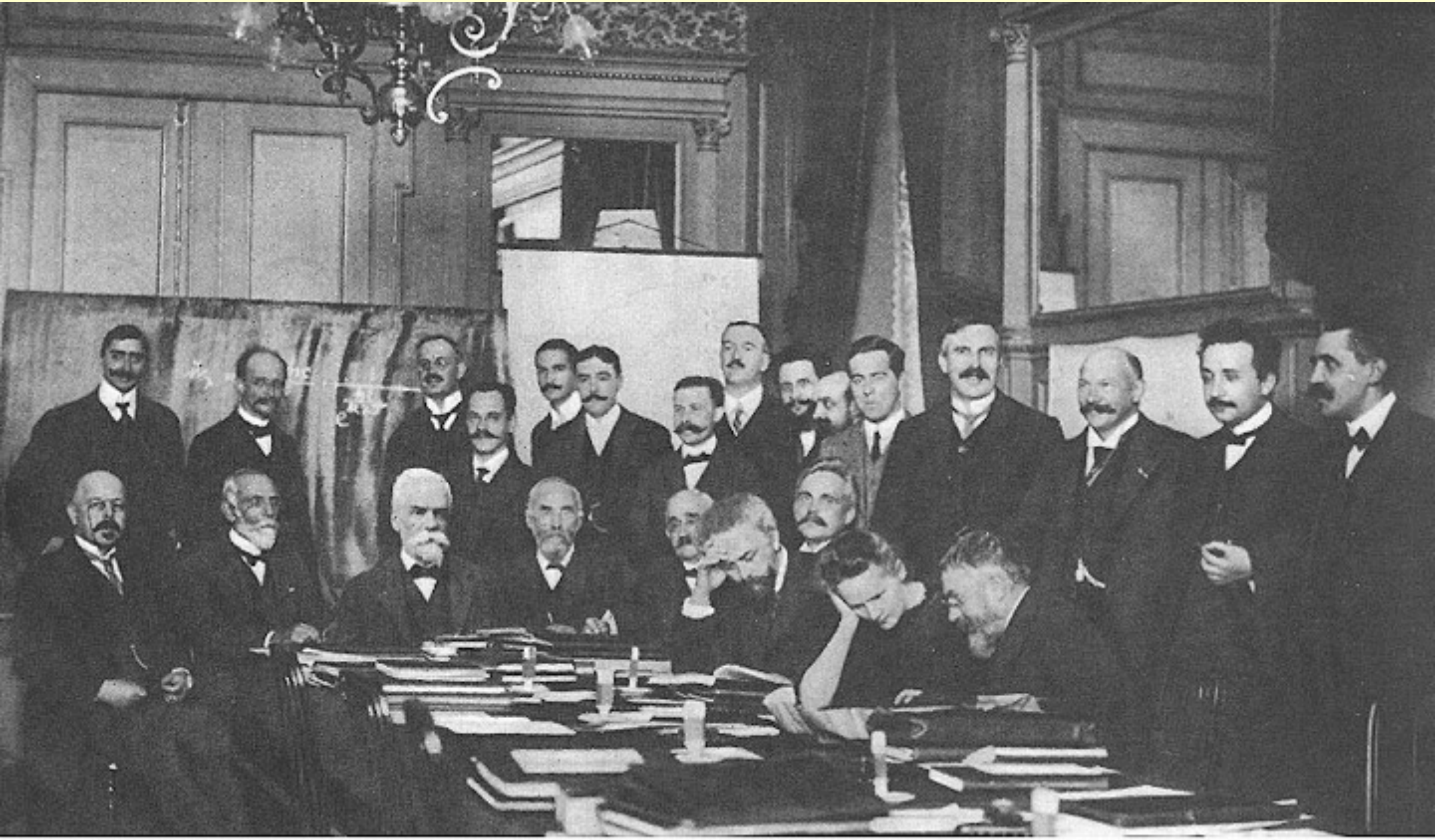




> ”...considering the enormous variation in the numbers of scattered particles, from 1 to 250000, the deviations from constancy of the ratio are probably well within the experimental error. The experiments, therefore, prove that the number of α particles scattered in a definite direction varies as cosec^4 φ/2.”

H. Geiger and E. Marsden, *Phil. Mag.* **25**, 604 (1913)

Solvay Conference 1911



GOLDSCHMIDT PLANCK RUBENS LINDEMANN HASENOHRL
NERNST BRILLOUIN SOMMERFELD M. DE BROGLIE HOSTELET
SOLVAY KNUDSEN HERZEN JEANS RUTHERFORD
LORENTZ WARBURG WIEN EINSTEIN LANGEVIN
PERRIN Madame CURIE POINCARÉ KAMERLINGH ONNES

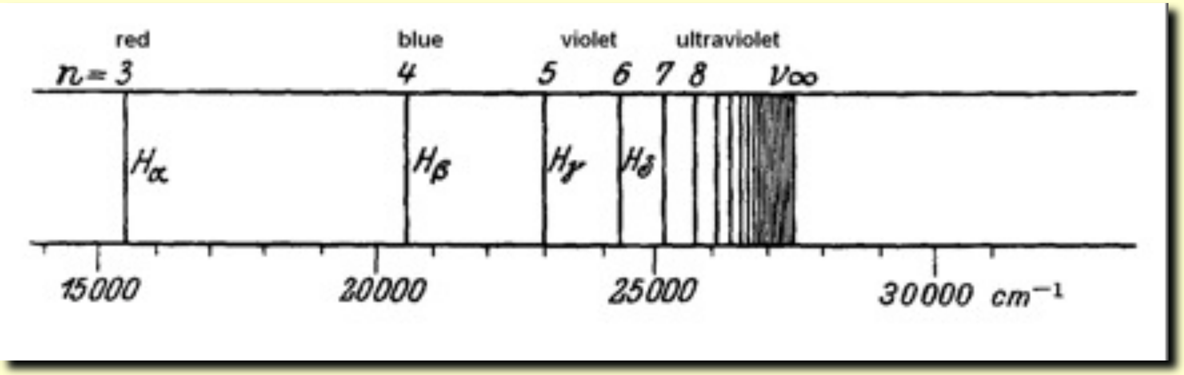
Solvay Conference 1913

The idea of the central atomic charge was proposed by Rutherford in the paper ”The Scattering of α and β Particles by Matter and the Structure of the Atom”, *Phil. Mag.* 21, 669-688 (May 1911). His aim was to explain the results obtained by Geiger and Marsden [*Proc. Roy. Soc.* 132, 495 (1909)]. The word ‘nucleus’ was first used by John Nicholson [*Phil. Mag.* 22, 864 (1911)]

Rutherford’s theory explained the scattering of α particles and hardly anything else, therefore it did not arouse much interest.

- First Solvay Conference on Physics (October 30 - November 3, 1911) - **not mentioned at all**
- Second Solvay Conference on Physics (October 27- 31, 1913) - **mentioned only** by Rutherford in a discussion after J. J. Thomson’s talk

- **Not mentioned** in Campbell’s *Modern Electrical Theory* (1913), Richardson’s *The Electron Theory of Matter* (1914); only **shortly mentioned** by Rutherford in his *Radioactive substances and their radiations* (1913)



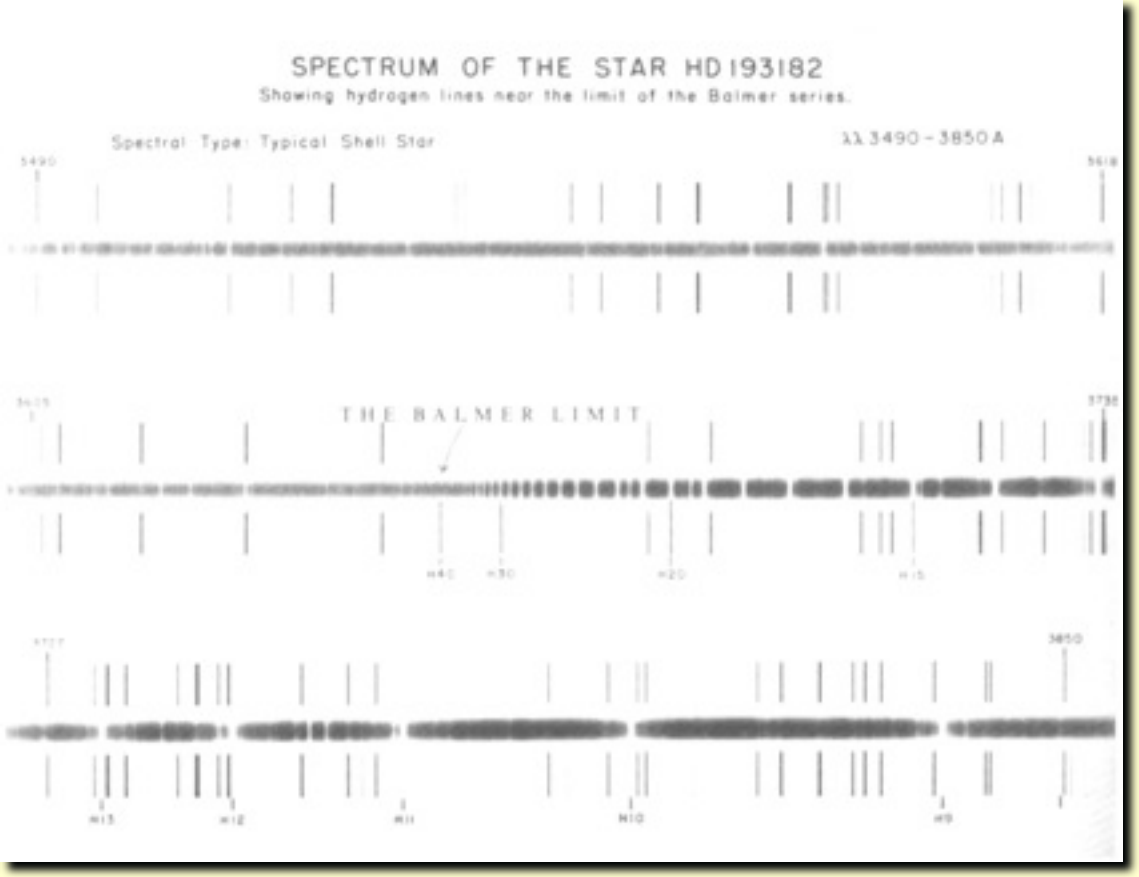
$$\lambda = bm^2/(m^2 - n^2)$$

$$n = 2,\ m = 3, 4, 5\ldots$$

$$b = 3645.6$$

Balmer's formula (1885)

Johann Balmer



SPECTRUM OF THE STAR HD193182

Showing hydrogen lines near the limit of the Balmer series.

Spectral Type: Typical Shell Star

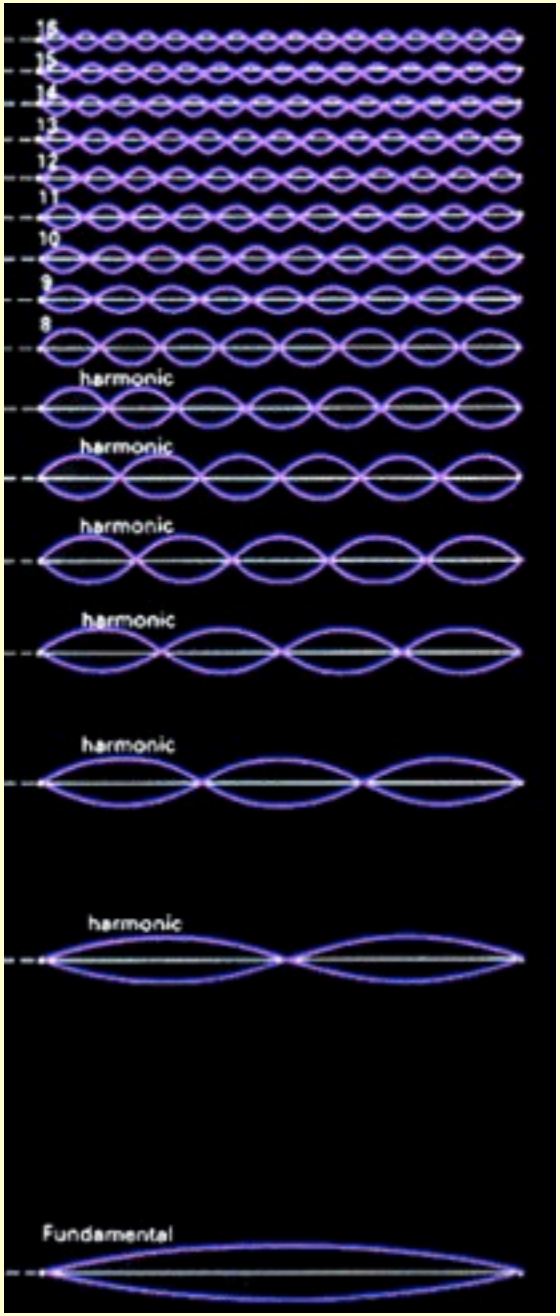
λλ 3490 - 3850 A

”The wavelengths of the first four hydrogen lines are obtained by multiplying the fundamental number b = 3645.6 in succession by the coefficients 9/5, 4/3, 25/21 and 9/8. At first it appears that these four coeffcients do not form a regular series; but if we multiply the numerators in the second and the fourth terms by 4 a consistent regularity is evident and the coefficients have for numerators the numbers 3^2, 4^2, 5^2 ,6^2, and for denominators a number that is less by 4. Hence I finally arrived at the present formula for the coefficients in the more general form: $m^2/(m^2 - n^2)$ in which m and n are whole numbers.”

Johann Balmer

Formula	Measurement	Difference
H_α 6562.08	6562.10	+0.02
H_β 4860.8	4860.74	–0.06
H_γ 4340	4340.1	+0.1
H_δ 4101.3	4101.2	–0.1

Balmer, *Ann.d. Phys. u. Chem*. (1885)



Spectral lines were seen as manifestation of the harmonic vibrations within atoms. Johnstone Stoney suggested that it is more convenient to use

$$1/\lambda \sim \nu$$

harmonic frequencies

$$\nu = k\, \nu_0$$

Combination principle:

One can determine from experimental values measured on a particular atom, a series of numbers T_n called spectral terms, such that every wavenumber corresponding to a spectral line of this atom is equal to the difference of two spectral terms

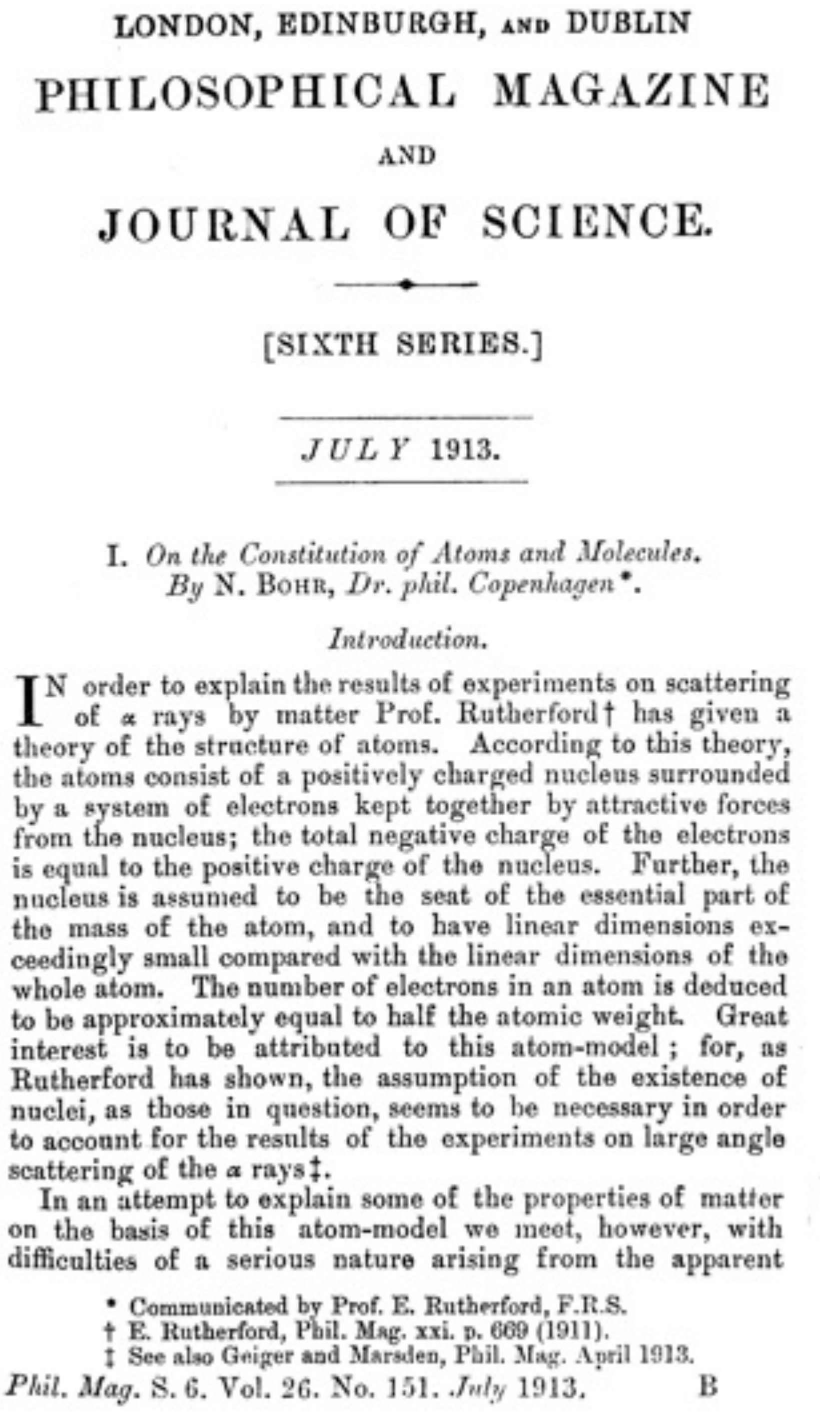
Walter Ritz

$$1/\lambda_{nm} = T_n - T_m$$

Law of Series Spectra, *Astrophysical Journal* **28**, 237 (Oct. 1908)

(used by Niels Bohr in his 1913 paper on the constitution of atoms)

Bohr’s planetary model of the atom



LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[SIXTH SERIES.]

JULY 1913.

I. *On the Constitution of Atoms and Molecules.*
By N. Bohr, *Dr. phil. Copenhagen**.

Introduction.

IN order to explain the results of experiments on scattering of α rays by matter Prof. Rutherford† has given a theory of the structure of atoms. According to this theory, the atoms consist of a positively charged nucleus surrounded by a system of electrons kept together by attractive forces from the nucleus; the total negative charge of the electrons is equal to the positive charge of the nucleus. Further, the nucleus is assumed to be the seat of the essential part of the mass of the atom, and to have linear dimensions exceedingly small compared with the linear dimensions of the whole atom. The number of electrons in an atom is deduced to be approximately equal to half the atomic weight. Great interest is to be attributed to this atom-model; for, as Rutherford has shown, the assumption of the existence of nuclei, as those in question, seems to be necessary in order to account for the results of the experiments on large angle scattering of the α rays‡.

In an attempt to explain some of the properties of matter on the basis of this atom-model we meet, however, with difficulties of a serious nature arising from the apparent

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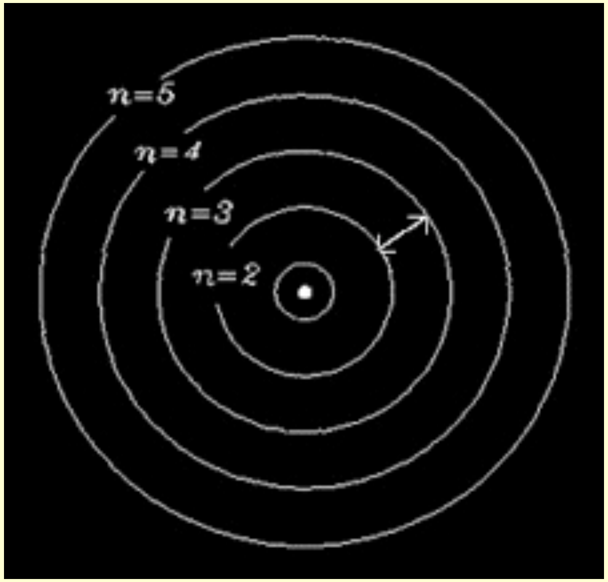
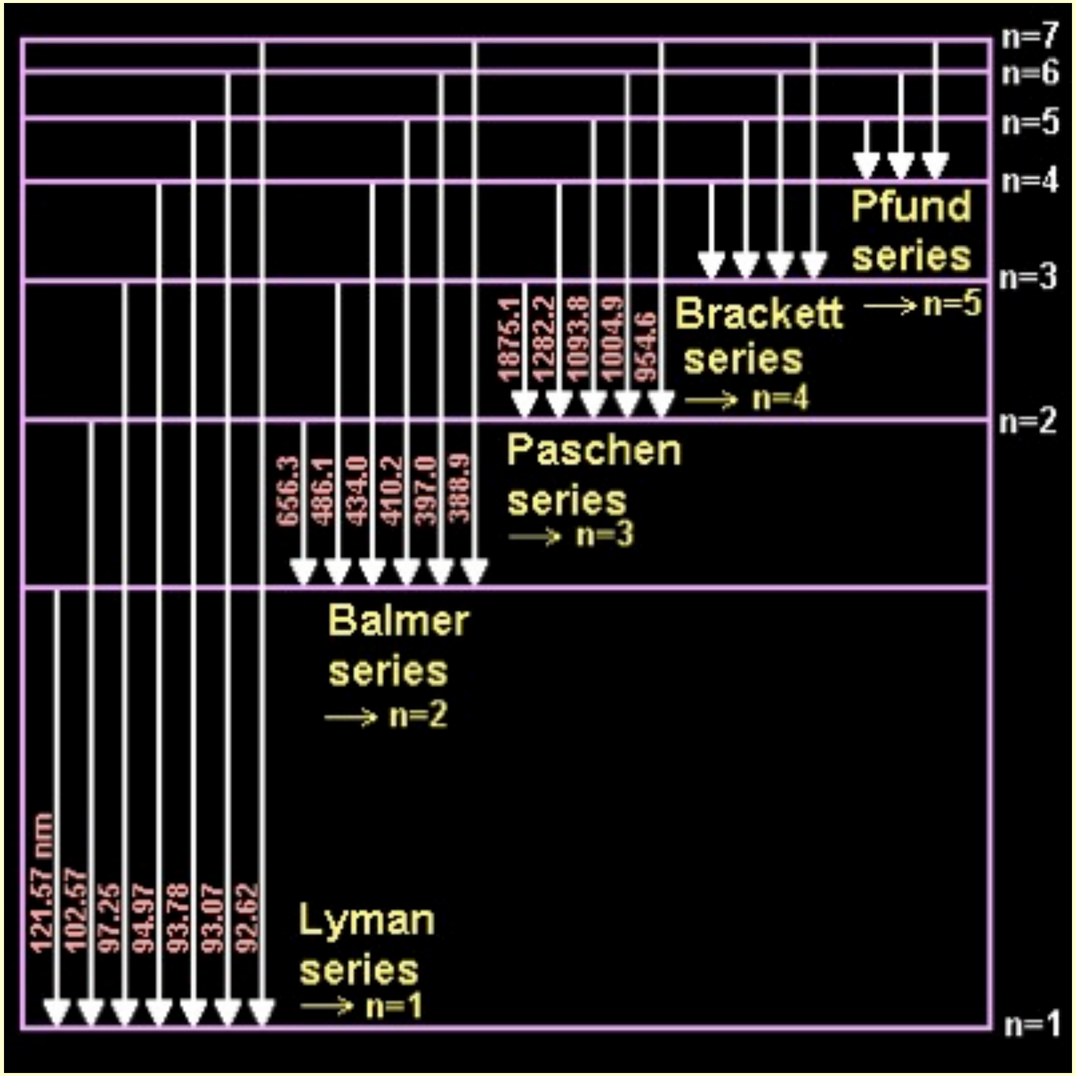
* Communicated by Prof. E. Rutherford, F.R.S.
† E. Rutherford, Phil. Mag. xxi. p. 669 (1911).
‡ See also Geiger and Marsden, Phil. Mag. April 1913.

Phil. Mag. S. 6. Vol. 26. No. 151. *July* 1913. B

Niels Bohr in 1917





The spectral lines are interpreted in the Bohr's model as radiation emitted in transitions of electrons between allowed orbits in which **the electrons do not radiate** (allowed energy levels)

Bohr found excellent description of the Balmer series

$$\lambda = hm^2/(m^2 - n^2) \quad n = 2,\ m = 3, 4, 5...$$

and of the Paschen series

$$\lambda = hm^2/(m^2 - n^2) \quad n = 3,\ m = 4, 5, 6...$$

and predicted an ultraviolet series

$$\lambda = hm^2/(m^2 - n^2) \quad n = 1,\ m = 2, 3, 4,...$$

which was found in 1914 by Theodore Lyman

Bohr also explained the series of spectral lines found in the spectrum of the star ζ Puppis as due to the ionized helium atom

Max Laue on Bohr’s model:

“That’s all nonsense; Maxwell’s equations are correct under all circumstances, and an electron orbiting around a positive nucleus is bound to radiate”

Carl Runge on Bohr’s idea:

“Well, such a nice man, and so intelligent. But this man has become completely crazy. This is the sheerest nonsense.”

“Bohr’s work on the quantum theory of the Balmer formula (in the *Phil. Mag.*) has driven me to despair. If this is the way to reach the goal, I must give up doing physics.”

(Paul Ehrenfest in a letter to Lorentz, August 1913)

British Association for the Advancement of Science, meeting in Birmingham, September 10-17, 1913

Niels Bohr was a participant and gave a brief account of his model during the discussion.

> "His scheme for the hydrogen atom assumes several stationary states for the atom, and the passage from one state to another involves the yielding of one quantum."
> (*Nature* **92**, 306, November 6, 1913)

Meeting of the Deutscher Naturforscher und Ärzte, Vienna, September 21-28, 1913

Bohr's model was not mentioned

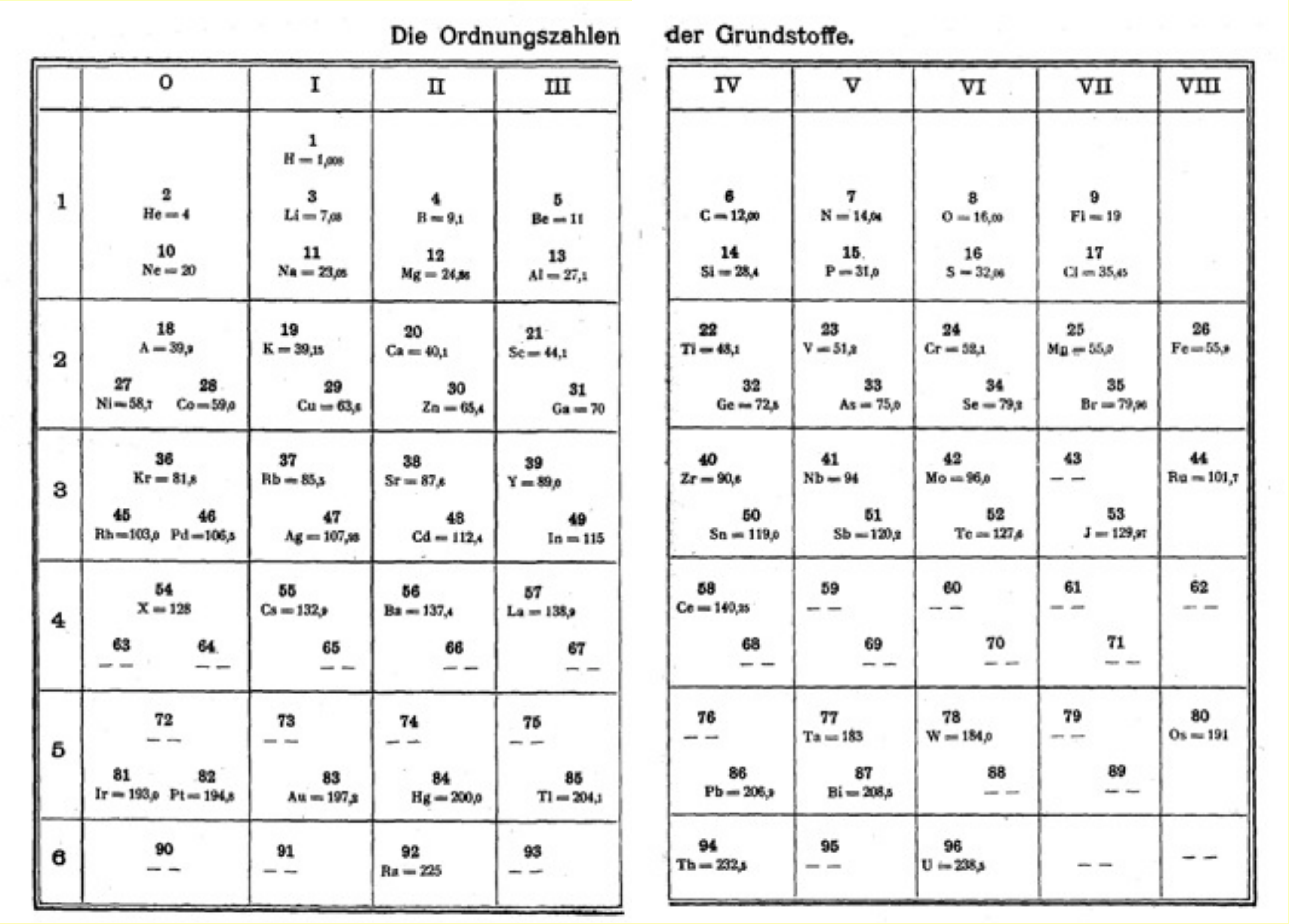
Second Solvay Conference, Brussels, October 27-31, 1913

Bohr's model was not mentioned

”Until quite recently, it seems to have been assumed implicitly by all those who had followed the development of the electron theory that the mass of an atom was the sum of the masses of the electrons contained in it and that the number of electrons in an atom (P) was given by the expression $P = A\ M/m$ where M is the mass of an atom of hydrogen, A the atomic weight, and m the mass of an electron...
In the present state of our knowledge no certain statement can be attained as to the whole number of the electrons in any atom, but the conclusion that it is such that the mass of the atom is the sum of the masses of the electrons contained in it is so attractive that it seems desirable to accept it provisionally in the absence of any conclusive evidence to the contrary....”

Norman R. Campbell, *Modern electrical theory* (1907)

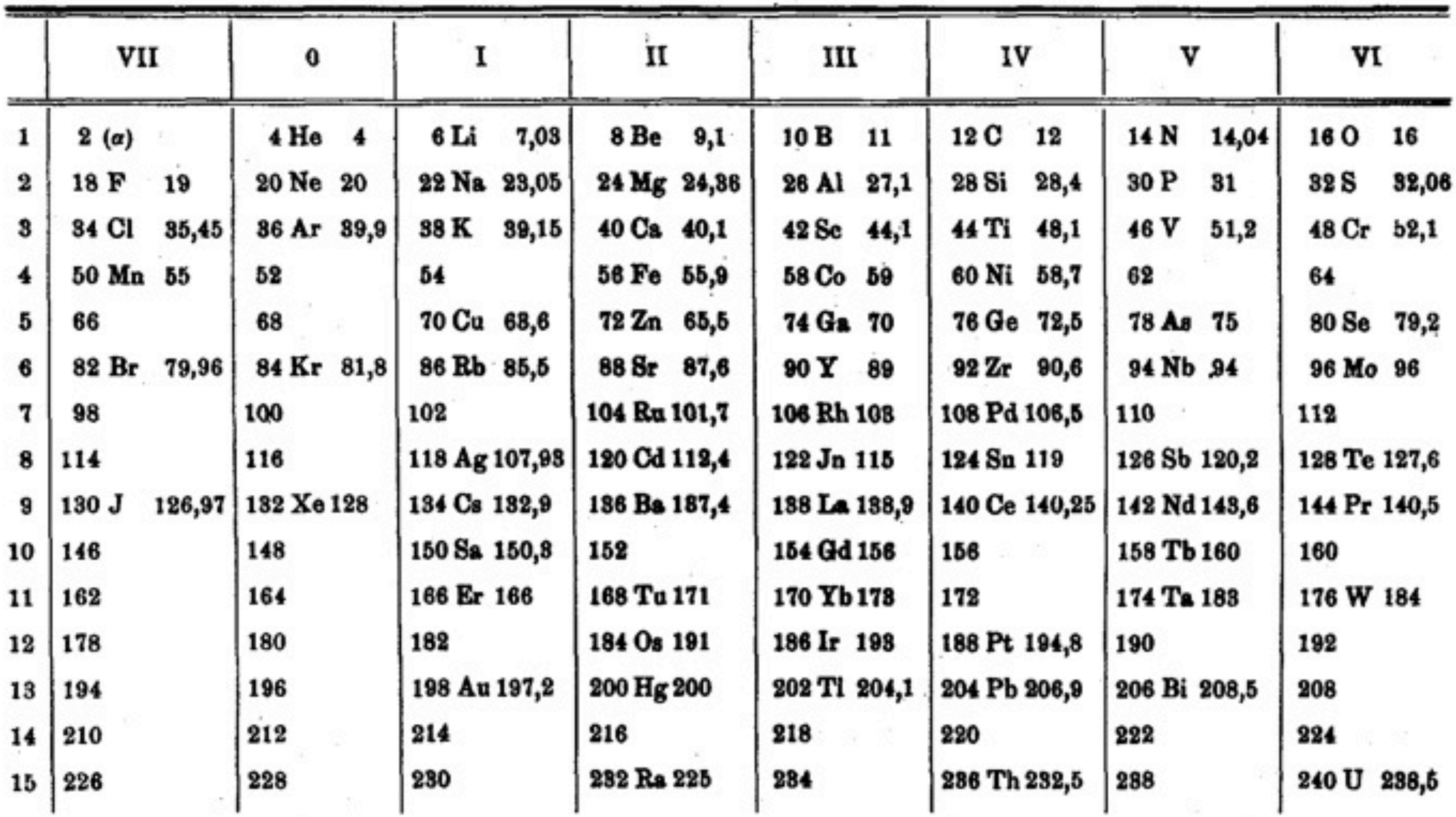
Periodic system of elements according to Rydberg (1906)



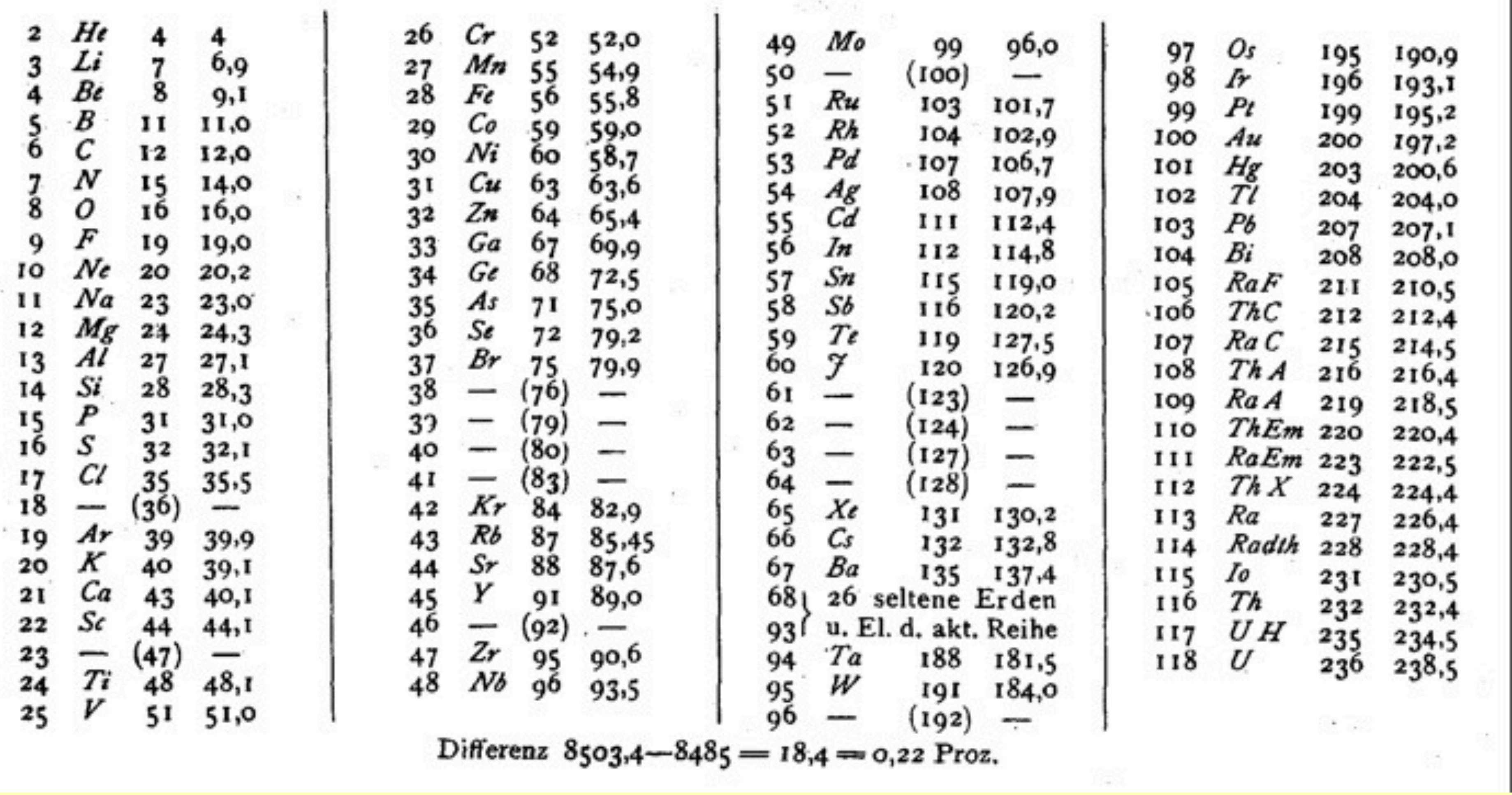
Die Ordnungszahlen der Grundstoffe.

	O	I	II	III	IV	V	VI	VII	VIII
1	2 He = 4 10 Ne = 20	1 H = 1,008 3 Li = 7,03 11 Na = 23,05	4 B = 9,1 12 Mg = 24,36	5 Be = 11 13 Al = 27,1	6 C = 12,00 14 Si = 28,4	7 N = 14,04 15 P = 31,0	8 O = 16,00 16 S = 32,06	9 Fl = 19 17 Cl = 35,45	
2	18 A = 39,9 27 Ni = 58,7 28 Co = 59,0	19 K = 39,15 29 Cu = 63,6	20 Ca = 40,1 30 Zn = 65,4	21 Sc = 44,1 31 Ga = 70	22 Ti = 48,1 32 Ge = 72,5	23 V = 51,2 33 As = 75,0	24 Cr = 52,1 34 Se = 79,2	25 Mg = 55,0 35 Br = 79,96	26 Fe = 55,9
3	36 Kr = 81,8 45 Rh = 103,0 46 Pd = 106,5	37 Rb = 85,5 47 Ag = 107,93	38 Sr = 87,6 48 Cd = 112,4	39 Y = 89,0 49 In = 115	40 Zr = 90,6 50 Sn = 119,0	41 Nb = 94 51 Sb = 120,2	42 Mo = 96,0 52 Tc = 127,6	43 — — 53 J = 129,97	44 Ru = 101,7
4	54 X = 128 63 — — 64 — —	55 Cs = 132,9 65 — —	56 Ba = 137,4 66 — —	57 La = 138,9 67 — —	58 Ce = 140,25 68 — —	59 — — 69 — —	60 — — 70 — —	61 — — 71 — —	62 — —
5	72 — — 81 Ir = 193,0 82 Pt = 194,8	73 — — 83 Au = 197,2	74 — — 84 Hg = 200,0	75 — — 85 Tl = 204,1	76 — — 86 Pb = 206,9	77 Ta = 183 87 Bi = 208,5	78 W = 184,0 88 — —	79 — — 89 — —	80 Os = 191
6	90 — —	91 — —	92 Ra = 225	93 — —	94 Th = 232,5	95 — —	96 U = 238,5	— —	— —

Periodic system of elements according to Van den Broek (1907)



	VII	0	I	II	III	IV	V	VI
1	2 (α)	4 He 4	6 Li 7,03	8 Be 9,1	10 B 11	12 C 12	14 N 14,04	16 O 16
2	18 F 19	20 Ne 20	22 Na 23,05	24 Mg 24,36	26 Al 27,1	28 Si 28,4	30 P 31	32 S 32,06
3	34 Cl 35,45	36 Ar 39,9	38 K 39,15	40 Ca 40,1	42 Sc 44,1	44 Ti 48,1	46 V 51,2	48 Cr 52,1
4	50 Mn 55	52	54	56 Fe 55,9	58 Co 59	60 Ni 58,7	62	64
5	66	68	70 Cu 63,6	72 Zn 65,5	74 Ga 70	76 Ge 72,5	78 As 75	80 Se 79,2
6	82 Br 79,96	84 Kr 81,8	86 Rb 85,5	88 Sr 87,6	90 Y 89	92 Zr 90,6	94 Nb ,94	96 Mo 96
7	98	100	102	104 Ru 101,7	106 Rh 103	108 Pd 106,5	110	112
8	114	116	118 Ag 107,93	120 Cd 112,4	122 Jn 115	124 Sn 119	126 Sb 120,2	128 Te 127,6
9	130 J 126,97	132 Xe 128	134 Cs 132,9	136 Ba 137,4	138 La 138,9	140 Ce 140,25	142 Nd 143,6	144 Pr 140,5
10	146	148	150 Sa 150,3	152	154 Gd 156	156	158 Tb 160	160
11	162	164	166 Er 166	168 Tu 171	170 Yb 173	172	174 Ta 183	176 W 184
12	178	180	182	184 Os 191	186 Ir 193	188 Pt 194,8	190	192
13	194	196	198 Au 197,2	200 Hg 200	202 Tl 204,1	204 Pb 206,9	206 Bi 208,5	208
14	210	212	214	216	218	220	222	224
15	226	228	230	232 Ra 225	234	236 Th 232,5	238	240 U 238,5



2	*He*	4	4
3	*Li*	7	6,9
4	*Be*	8	9,1
5	*B*	11	11,0
6	*C*	12	12,0
7	*N*	15	14,0
8	*O*	16	16,0
9	*F*	19	19,0
10	*Ne*	20	20,2
11	*Na*	23	23,0
12	*Mg*	24	24,3
13	*Al*	27	27,1
14	*Si*	28	28,3
15	*P*	31	31,0
16	*S*	32	32,1
17	*Cl*	35	35,5
18	—	(36)	—
19	*Ar*	39	39,9
20	*K*	40	39,1
21	*Ca*	43	40,1
22	*Sc*	44	44,1
23	—	(47)	—
24	*Ti*	48	48,1
25	*V*	51	51,0
26	*Cr*	52	52,0
27	*Mn*	55	54,9
28	*Fe*	56	55,8
29	*Co*	59	59,0
30	*Ni*	60	58,7
31	*Cu*	63	63,6
32	*Zn*	64	65,4
33	*Ga*	67	69,9
34	*Ge*	68	72,5
35	*As*	71	75,0
36	*Se*	72	79,2
37	*Br*	75	79,9
38	—	(76)	—
39	—	(79)	—
40	—	(80)	—
41	—	(83)	—
42	*Kr*	84	82,9
43	*Rb*	87	85,45
44	*Sr*	88	87,6
45	*Y*	91	89,0
46	—	(92)	—
47	*Zr*	95	90,6
48	*Nb*	96	93,5
49	*Mo*	99	96,0
50	—	(100)	—
51	*Ru*	103	101,7
52	*Rh*	104	102,9
53	*Pd*	107	106,7
54	*Ag*	108	107,9
55	*Cd*	111	112,4
56	*In*	112	114,8
57	*Sn*	115	119,0
58	*Sb*	116	120,2
59	*Te*	119	127,5
60	*J*	120	126,9
61	—	(123)	—
62	—	(124)	—
63	—	(127)	—
64	—	(128)	—
65	*Xe*	131	130,2
66	*Cs*	132	132,8
67	*Ba*	135	137,4
68 }	26 seltene Erden		
93 }	u. El. d. akt. Reihe		
94	*Ta*	188	181,5
95	*W*	191	184,0
96	—	(192)	—
97	*Os*	195	190,9
98	*Ir*	196	193,1
99	*Pt*	199	195,2
100	*Au*	200	197,2
101	*Hg*	203	200,6
102	*Tl*	204	204,0
103	*Pb*	207	207,1
104	*Bi*	208	208,0
105	*RaF*	211	210,5
106	*ThC*	212	212,4
107	*Ra C*	215	214,5
108	*Th A*	216	216,4
109	*Ra A*	219	218,5
110	*ThEm*	220	220,4
111	*RaEm*	223	222,5
112	*Th X*	224	224,4
113	*Ra*	227	226,4
114	*Radth*	228	228,4
115	*Io*	231	230,5
116	*Th*	232	232,4
117	*U H*	235	234,5
118	*U*	236	238,5

Differenz 8503,4—8485 = 18,4 = 0,22 Proz.

Periodic system of elements
according to Van den Broek (January, 1913)

Antonius Van den Broek

1. The charge of the nucleus equals the number of the element in the Mendeleev periodic system

2. The atomic weight of an element is approximately two times larger that its number in the periodic system, hence the nucleus must contain electrons to compensate the additional positive charge

Nature **92**, 372 (1913)

Antonius Van den Broek
Intra-atomic Charge

”In a previous letter to *Nature* (July 20, 1911, p. 78) the hypothesis was proposed that the atomic weight being equal to about twice the intra-atomic charge.... Charges being known only very roughly (probably correct to 20 per cent), and the number of the last element Ur in the [periodic] series not being equal even approximately to half its atomic weight, either the number of elements in the Mendeleeff’s system is not correct (that was supposed to be the case in the first letter), or the intra-atomic charge for the elements at the end of the series is much smaller than that deduced from the experiment (about 200 for Au)...”

Nature **92**, 372 (November 27, 1913)

Intra-atomic Charge

”Now, according to Rutherford the ratio of the scattering of α particles per atom divided by the square of the charge must be constant. Geiger and Marsden (*Phil. Mag*. XXV, pp. 617 and 618) putting the nuclear charge proportional to the atomic weight, found values, however, showing not constancy, but systematic deviations from (mean values) 3.885 for Cu to 3.25 for Au. If now in these values the number *M* of the place each element occupies in Mendeleeff’s series is taken instead of *A*, the atomic weight, we get a real constant (18.7 ± 0.3); hence the hypothesis proposed holds good for Mendeleeff’s series, but the nuclear charge is not equal to half the atomic weight. Should thus the mass of the atom consist for by far the greatest part of α particles, then the nucleus must contain electrons to compensate this extra charge...”

Antonius Van den Broek

Nature **92**, 372 (November 27, 1913)

”Should the α particle be composed of 4(H$^+$) + 2 electrons, then the number of nuclear electrons should be for U 142, that of the positive units 238, and, 380 particles occupying about 2.7•10^{-35} c.cm., the positive unit must be of equal size, if not identical with the electron (0.5•10^{-37}), but in a different state.”

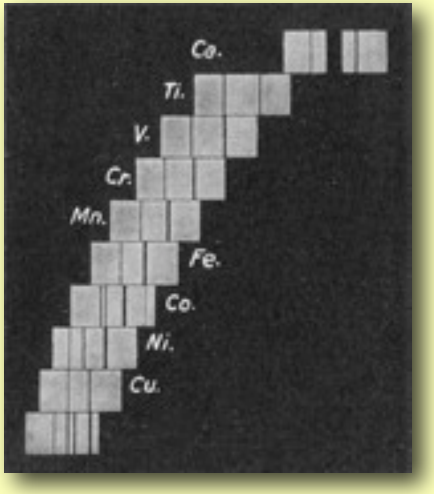
Antonius Van den Broek - On Nuclear Electrons, *Phil. Mag.* (1913)

”...the nucleus, though of minute dimensions, is in itself a very complex system consisting of a number of positively and negatively charged bodies bound together by intense electric forces...”

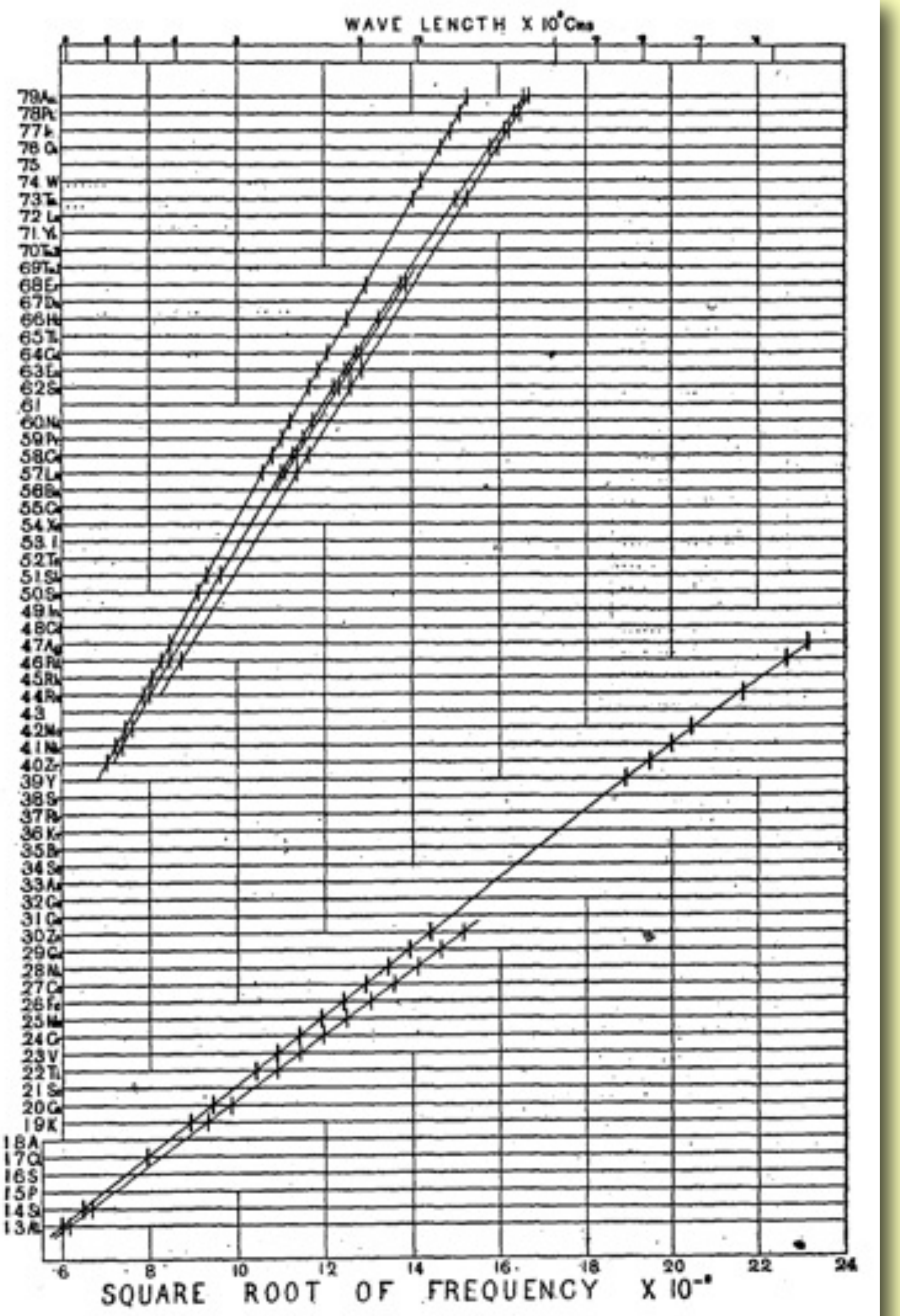
Ernest Rutherford, *Scientia*, 16, 337 (1914)

Henry Moseley (1887-1915)

$$\boxed{v = a\,(Z - \sigma)^2}$$



H. G. J. Moseley,
Phil. Mag. 26, 1024 (1913)



”We have here a proof that there is in the atom a fundamental quantity, which increases by regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus, of the existence of which we already have definite proof. Rutherford has shown, from the magnitude of the scattering of α particles by matter, that this nucleus carries a + charge approximately equal to that of $A/2$ electrons, where A is the atomic number. Barkla, from the scattering of X rays by matter, has shown that the number of electrons in an atom is roughly $A/2$, which for an electrically neutral atoms comes to the same thing. Now atomic weights increase on the average by about 2 units at a time, and this strongly suggests the view that N increases from atom to atom always by a single electronic unit. We are therefore led by experiment to the view that N is the same as the number of the place occupied by the element in the periodic system...This theory was originated by Broek and since used by Bohr.”

H. G. J. Moseley, *Phil. Mag.* **26**, 1024 (1913)

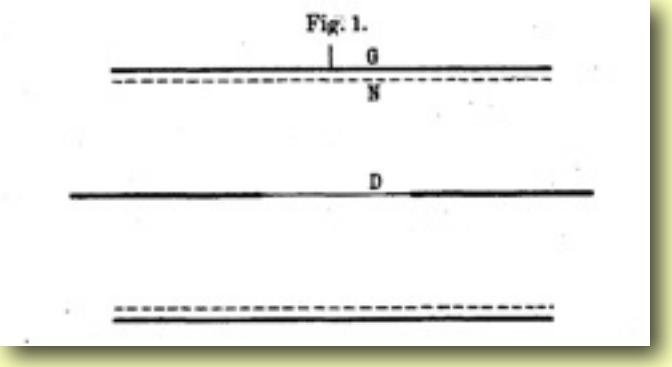
”The original suggestion of van de Broek that the charge of the nucleus is equal to the atomic number and not to half the atomic weight seems to me very promising. This idea has already been used by Bohr in his theory of the constitution of atoms. The strongest and most convincing evidence in support of this hypothesis will be found in a paper by Moseley in *Philosophical Magazine* of this month. He there shows that the frequency of the X-radiations from a number of elements can be simply explained if the number of unit charges on the nucleus is equal to the atomic number. It would appear that the charge of the nucleus is the fundamental constant which determines the physical and chemical properties of the atom, while the atomic weight, although it approximately follows the order of the nuclear charge, is probably a complicated function of the latter depending on the detailed structure of the nucleus.”

Rutherford, *Nature* 92, 423 (December 11, 1913)

Franck-Hertz experiment

James Franck

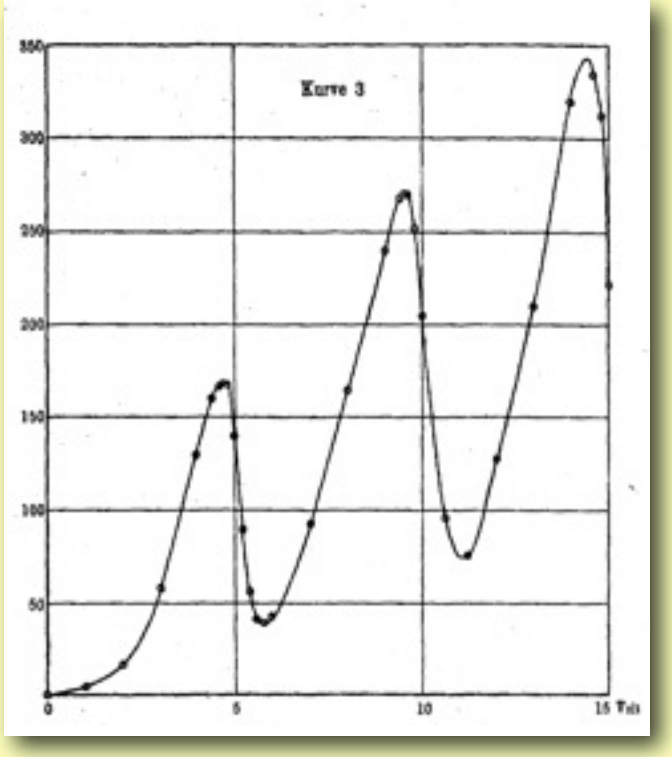
Gustav Hertz



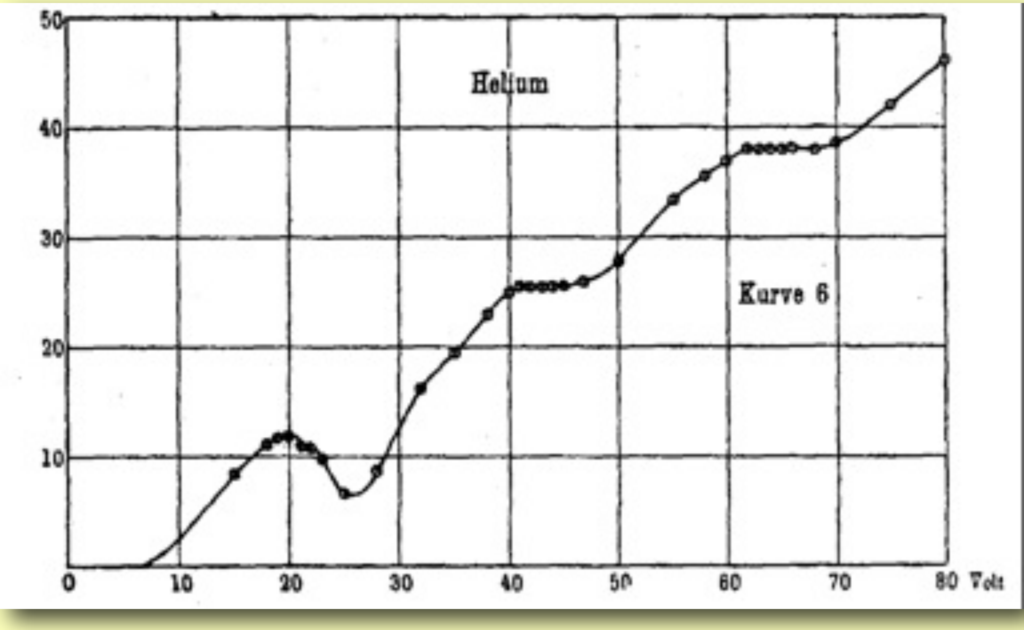
”The apparatus used in this investigation and in the final measurement of the ionization potential is shown in Figure 1. D is a platinum wire with a thin central section which could be brought to incandescence by a current. N is a fine cylindrical platinum wire mesh with a 4-cm radius surrounding D, and G is a cylindrical platinum foil, which is separated from N by 1 to 2 mm. G was grounded through a galvanometer. Rings of platinum foil were embedded in the glass covering to prevent any current from flowing to the galvanometer from parts of the wire carrying the voltage. Besides glass and platinum, the apparatus contained no fixed parts. All leads were fused into the glass.
...It was found that the electrons are reflected without energy loss from the mercury atoms as long as their velocities correspond to a drop through less than 5 volts...”

Collisions between electrons and mercury vapor molecules and the ionization potential of such molecules, *Verhand. Deutsch. Physik. Ges.*, **16**, 457 (1914)

Franck-Hertz experiment



Results for mercury



Results for helium

”The values for the spacings between any two successive maxima all lie between 4.8 i 5.0 volts, so that we may take 4.9 volts as the ionization potential of mercury vapor...”

James Franck

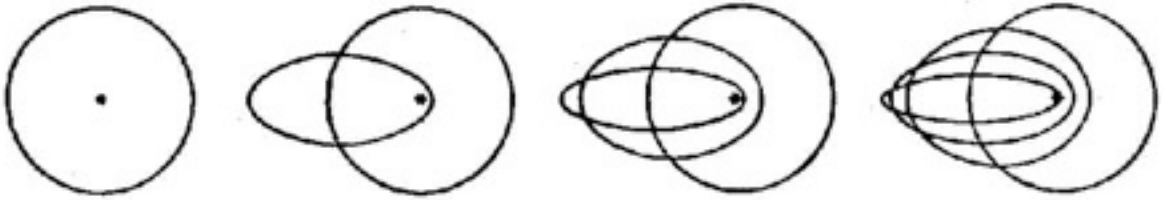
Gustav Hertz

”...it is not possible to make the assumption, as Bohr has done recently, that in helium the 20.5 volt beams and in mercury the 4.9 volt beams lead only to secondary ionization, such that the short-wavelength radiation [resulting from inelastic collisions] causes a photoelectric effect at the electrodes or at the impurities present in the gas.”
James Franck, Gustav Hertz (1916)

”Franck and Hertz assume that 4.9 volts corresponds to the energy necessary to remove an electron from the mercury atom, but it seems that their experiments may possibly be consistent with the assumption that this voltage correspond only to the transition from the normal state to some other stationary state of the neutral atom...”
Niels Bohr (1915)

Arnold Sommerfeld
(1868-1951)
Niels Bohr
(1885-1962)

Sommerfeld extended Bohr’s model by introducing two additional quantum numbers and explaining the fine structrure of the H_α line
[*Ann. d. Physik* **51**, 94, 125 (1916)]



ATOMBAU
UND
SPEKTRALLINIEN

Von
Arnold Sommerfeld
Professor der Theoretischen Physik an der Universität München

Mit 103 Abbildungen

Braunschweig 1919
Druck und Verlag von Friedr. Vieweg & Sohn

Wojciech (Adalbert) Rubinowicz

(1889-1974)

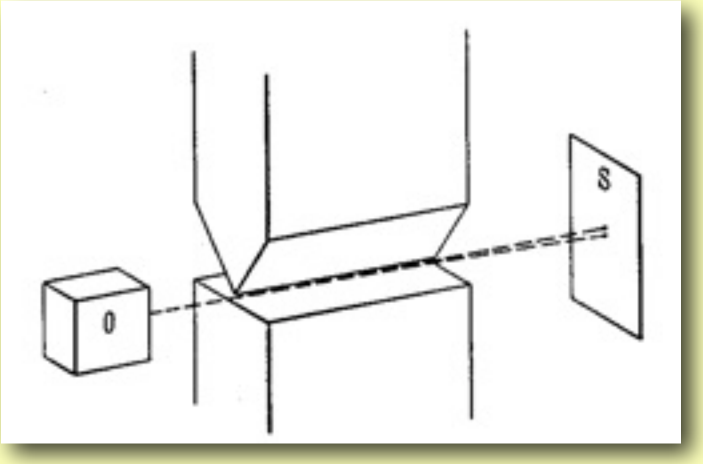
Selection rules $\Delta l = \pm 1$

Bohrsche Frequenzbedienung und Erhaltung des Impulsmomentum, Physikalische Zeitschrift **19**, 441-465, 465-474 (1918).

In modern terminology: it was the first attempt to determine the spin of the photon

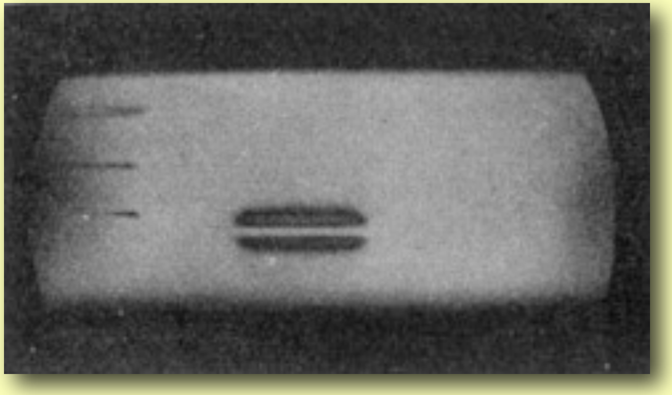
The Stern-Gerlach experiment (1921)

Otto Stern (1888-1969)



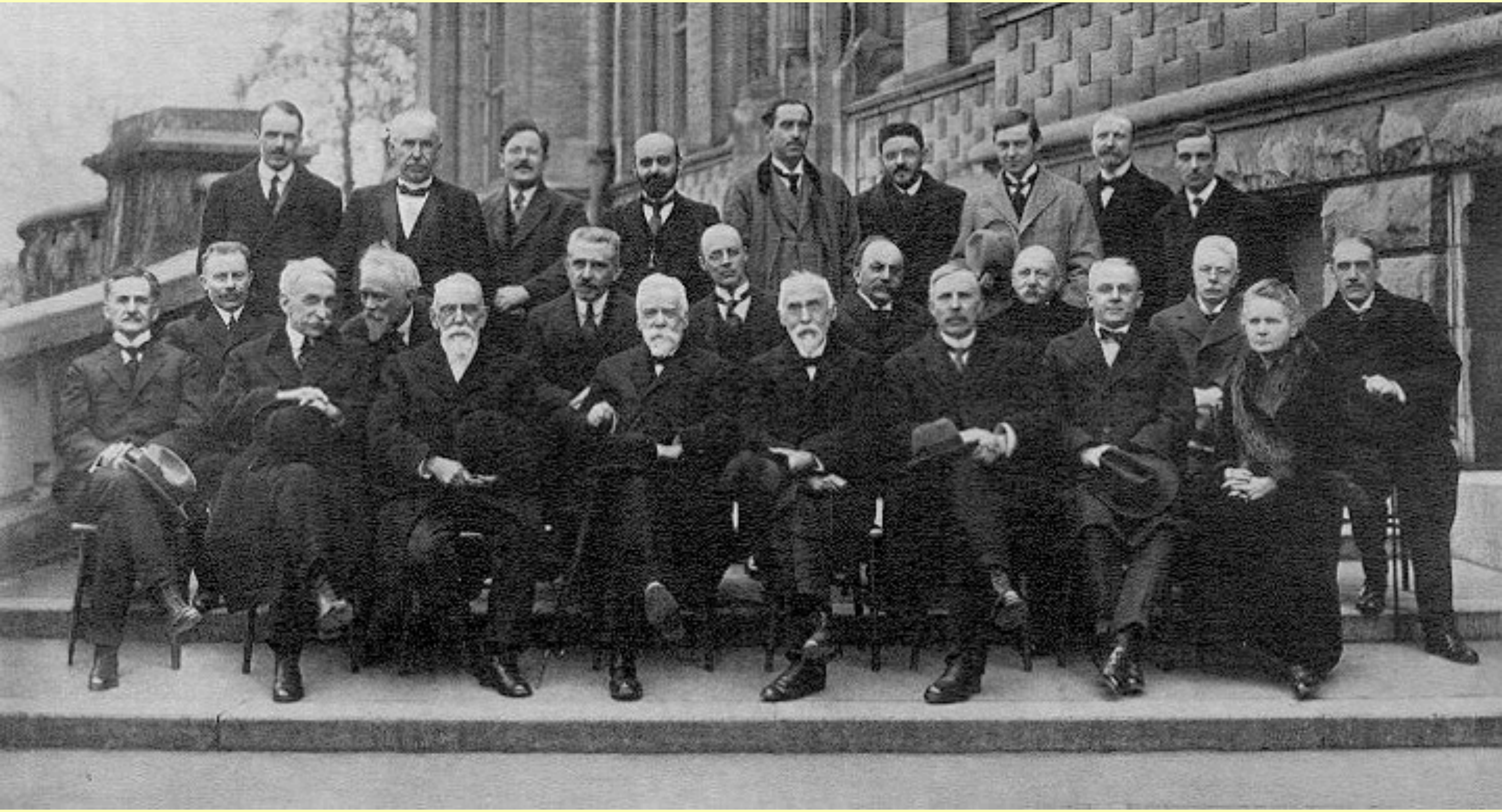
Experimental scheme

Walther Gerlach (1889-1979)

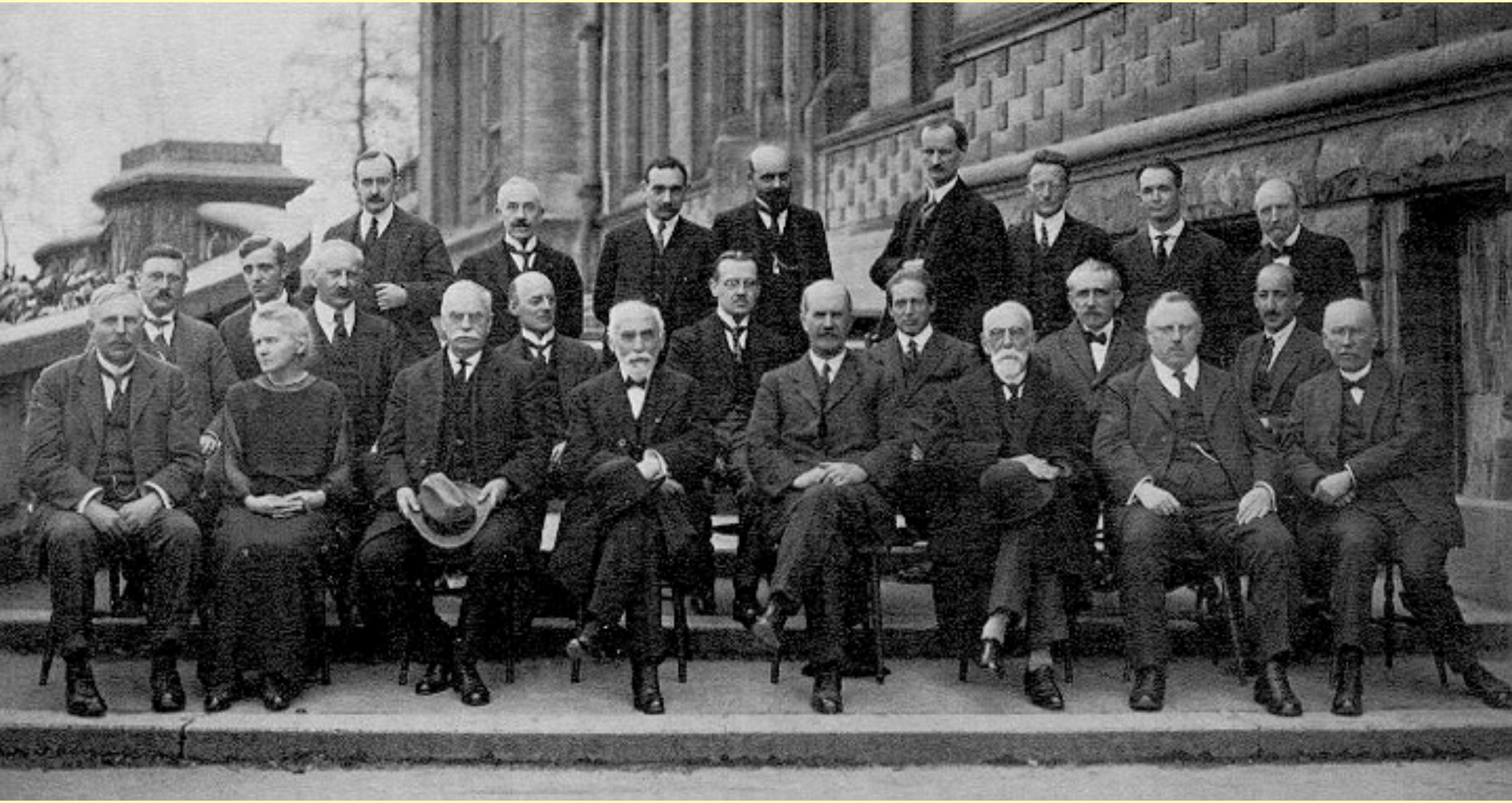


The results

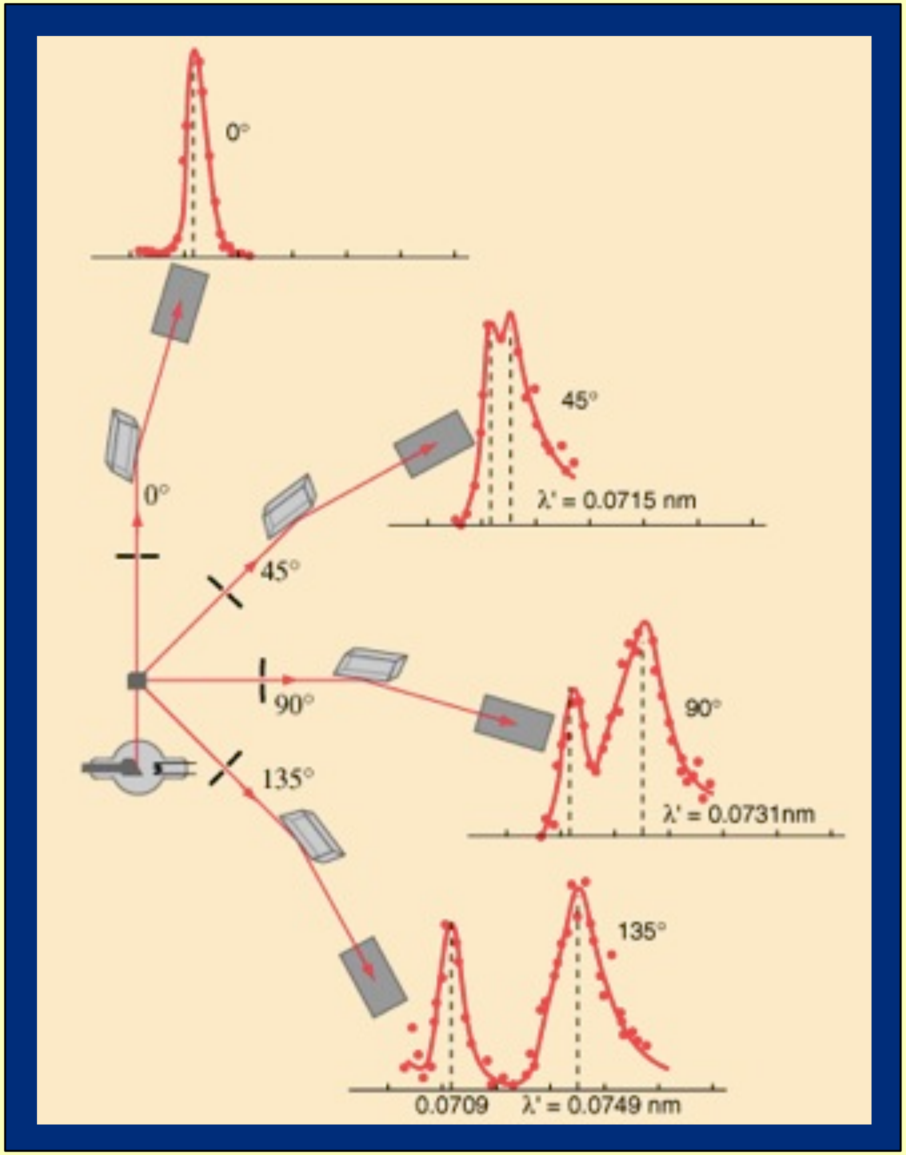
Solvay Conference 1921

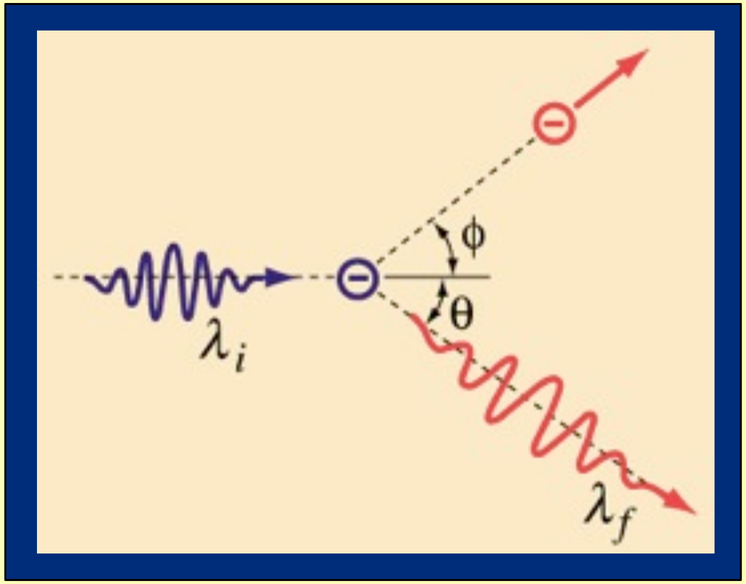


Solvay Conference 1924

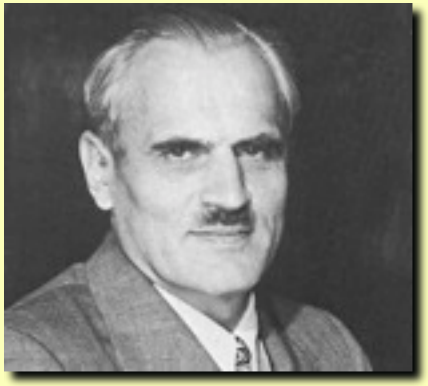


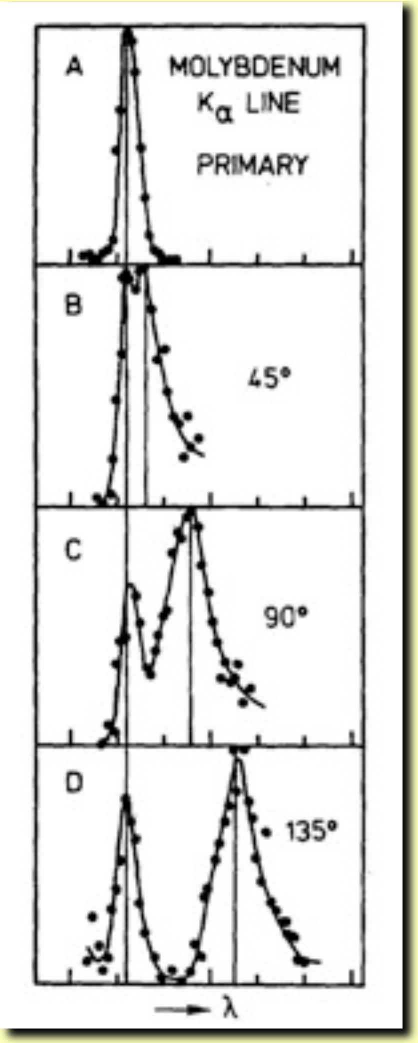
Compton effect

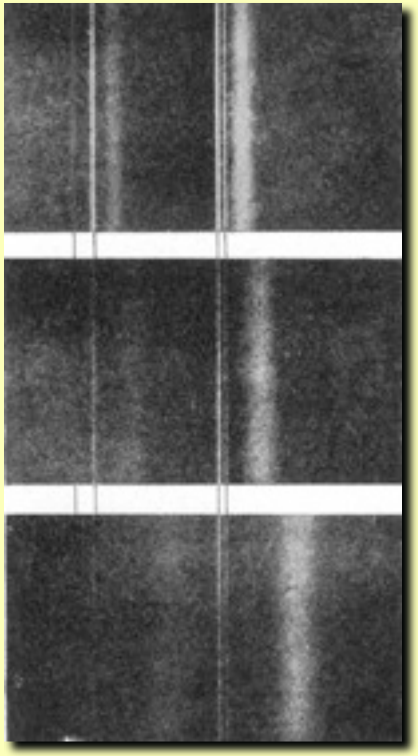


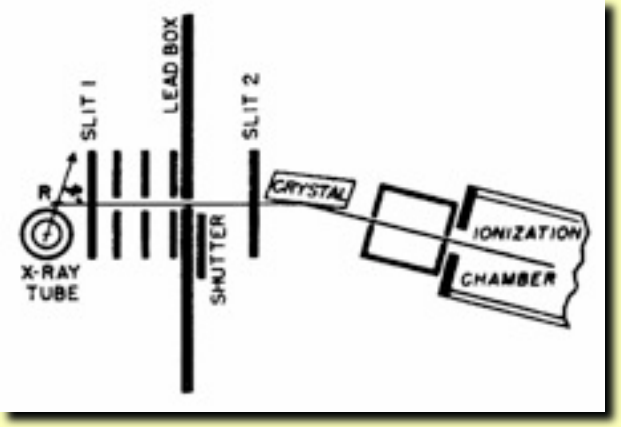


Arthur Holly Compton

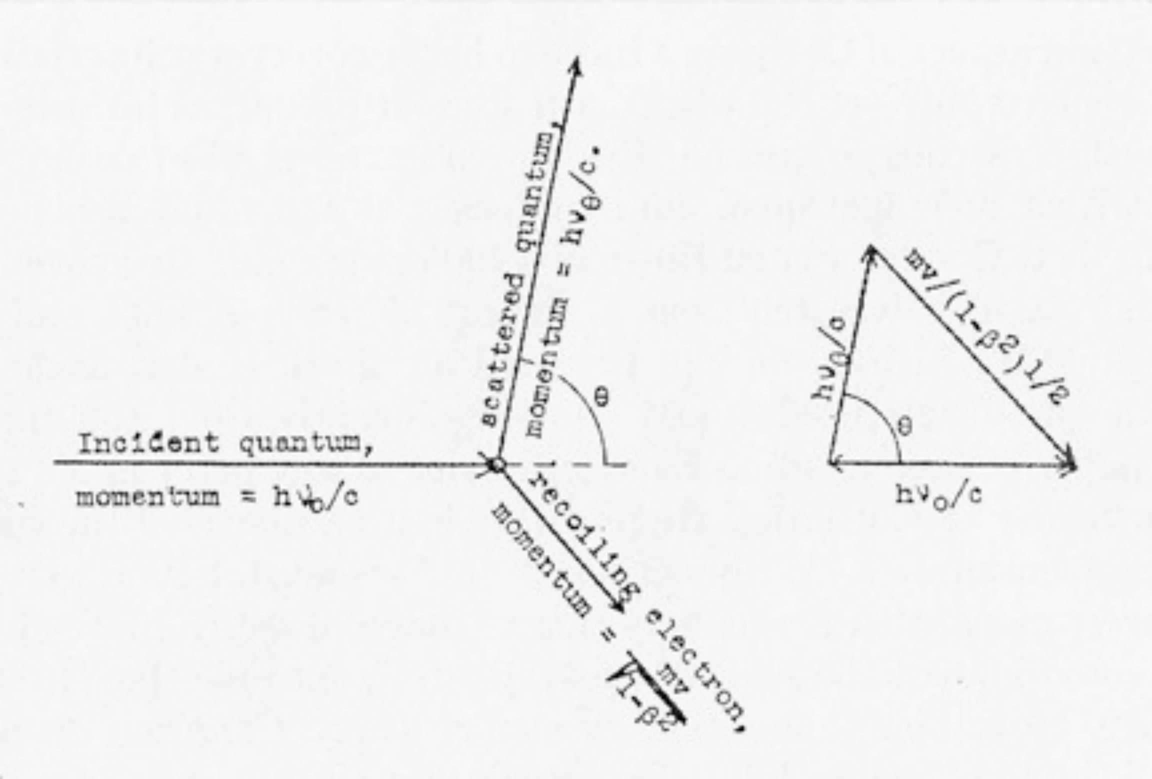








Arthur Holly Compton (1892-1962)



Compton’s vector diagram for the scattering of a light quantum on a free electron [*Phys.Rev.* **24**, 483 (1923)]

The crisis of the quantum theory

”The hypothesis of light quanta...is not able to throw light on the nature of radiation."
Bohr, Nobel lecture (1922)

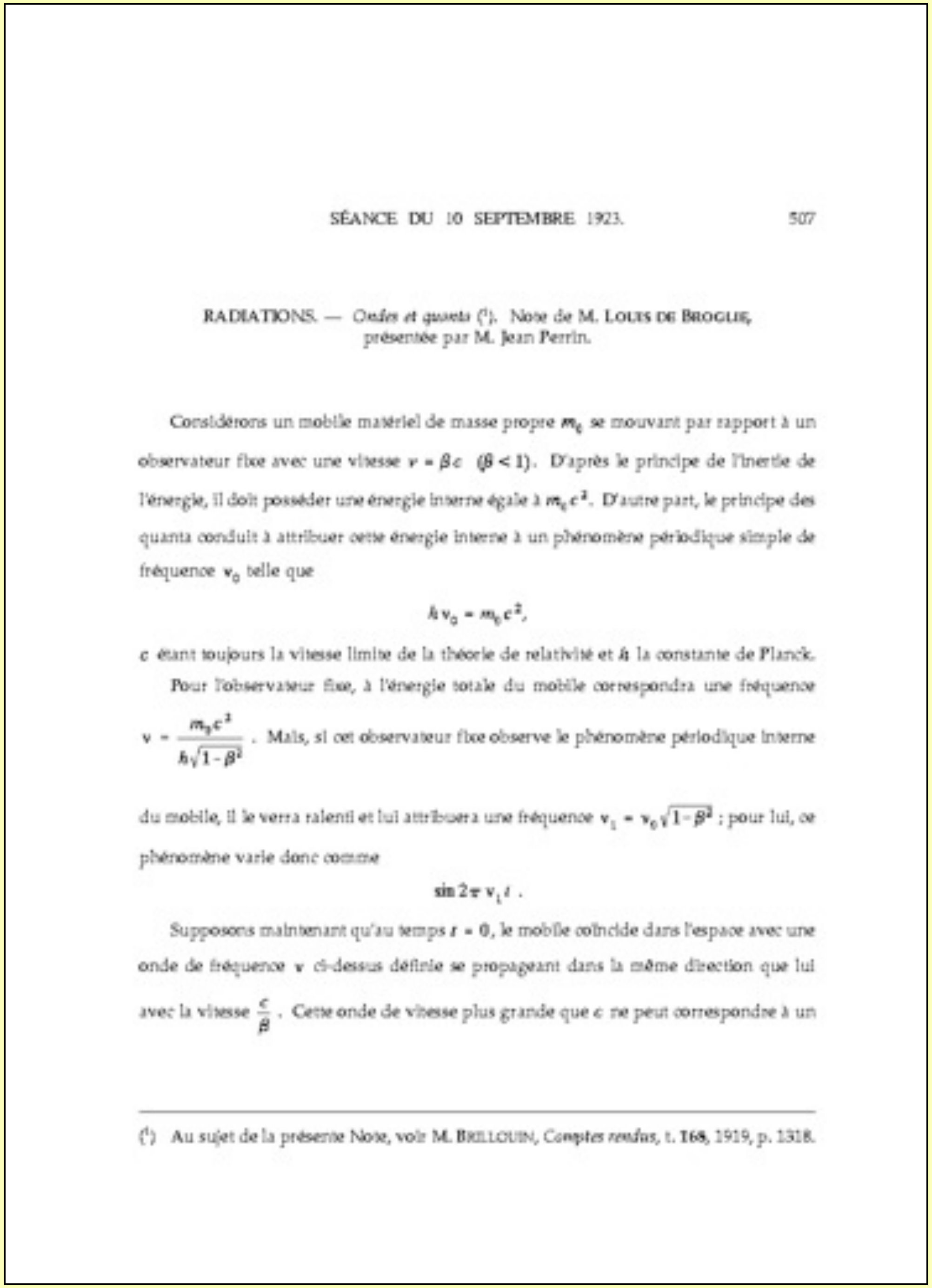
”A general description of phenomena, in which the laws of the conservation of energy and momentum retain in detail their validity in their classical formulation, cannot be carried through... the conservation of energy, as defined by means of classical conceptions, seems at once to be excluded."
Bohr (1923)

The crisis of the quantum theory

”We abandon any attempt at a casual connexion between the transition in distant atoms, and especially a direct application of the principles of conservation of energy and momentum, so characteristic of classical theories... Not only conservation of energy... but also conservation of momentum [reduce to] a statistical law."
Bohr, **Kramers, and Slater** (1924)

In 1925 counter (coincidence) experiments (**Bothe** and **Geiger**) and photographs from Wilson’s chamber (**Compton** and **Simon**) confirmed the validity of the conservation of energy and momentum in individual interactions.

”There is nothing else to do than to give our revolutionary efforts as honorable funeral as possible” (Bohr, 1925)



SÉANCE DU 10 SEPTEMBRE 1923. 507

RADIATIONS. — *Ondes et quanta* (1). Note de M. **Louis de Broglie**, présentée par M. Jean Perrin.

Considérons un mobile matériel de masse propre m_0 se mouvant par rapport à un observateur fixe avec une vitesse $v = \beta c$ $(\beta < 1)$. D'après le principe de l'inertie de l'énergie, il doit posséder une énergie interne égale à $m_0 c^2$. D'autre part, le principe des quanta conduit à attribuer cette énergie interne à un phénomène périodique simple de fréquence ν_0 telle que

$$h \nu_0 = m_0 c^2,$$

c étant toujours la vitesse limite de la théorie de relativité et h la constante de Planck.

Pour l'observateur fixe, à l'énergie totale du mobile correspondra une fréquence $\nu = \frac{m_0 c^2}{h\sqrt{1-\beta^2}}$. Mais, si cet observateur fixe observe le phénomène périodique interne du mobile, il le verra ralenti et lui attribuera une fréquence $\nu_1 = \nu_0 \sqrt{1-\beta^2}$; pour lui, ce phénomène varie donc comme

$$\sin 2\pi \nu_1 t .$$

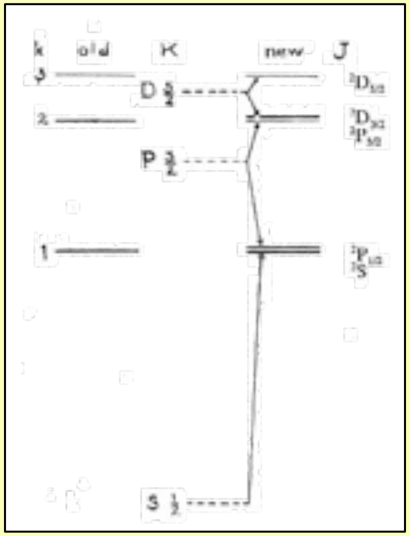
Supposons maintenant qu'au temps $t = 0$, le mobile coïncide dans l'espace avec une onde de fréquence ν ci-dessus définie se propageant dans la même direction que lui avec la vitesse $\frac{c}{\beta}$. Cette onde de vitesse plus grande que c ne peut correspondre à un

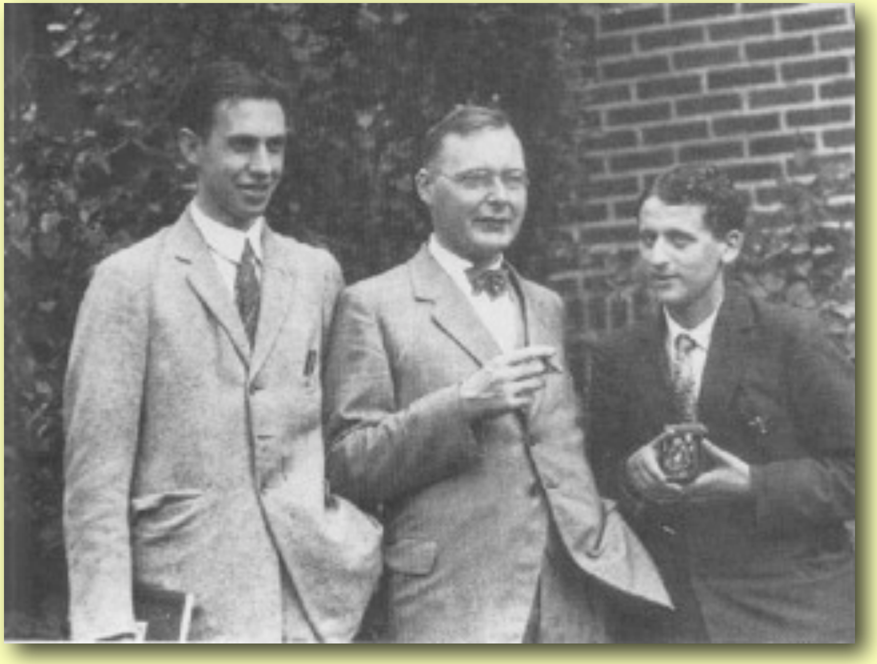
---

(1) Au sujet de la présente Note, voir M. **Brillouin**, *Comptes rendus*, t. **168**, 1919, p. 1318.

Louis de Broglie

Spinning Electrons and the Structure of Spectra, *Nature,* **117,** 264 (1926)

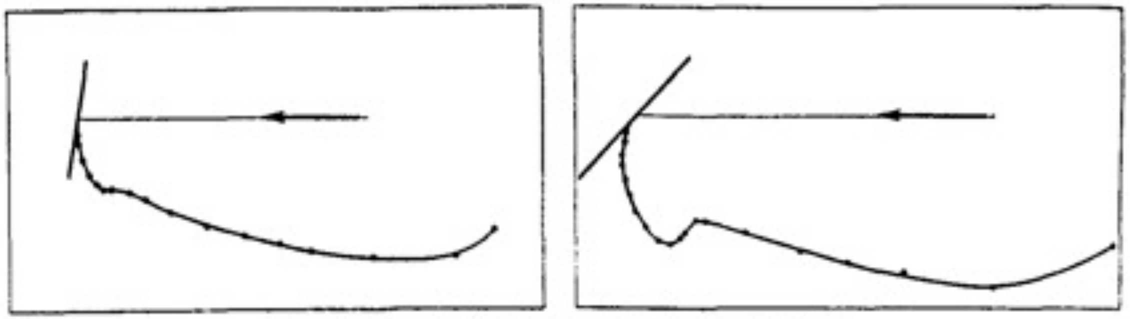




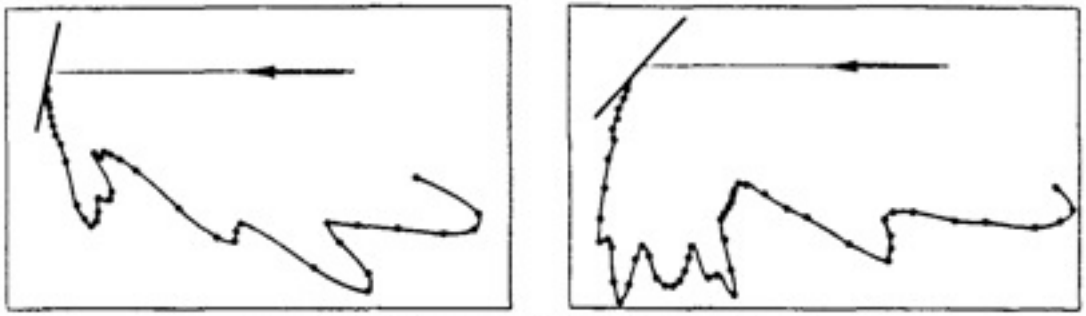
George Uhlenbeck, Hendrik Kramers
and Samuel Goudsmit

”You are both young enough to be able to afford a stupidity like that” - Ehrenfest to Uhlenbeck and Goudsmit

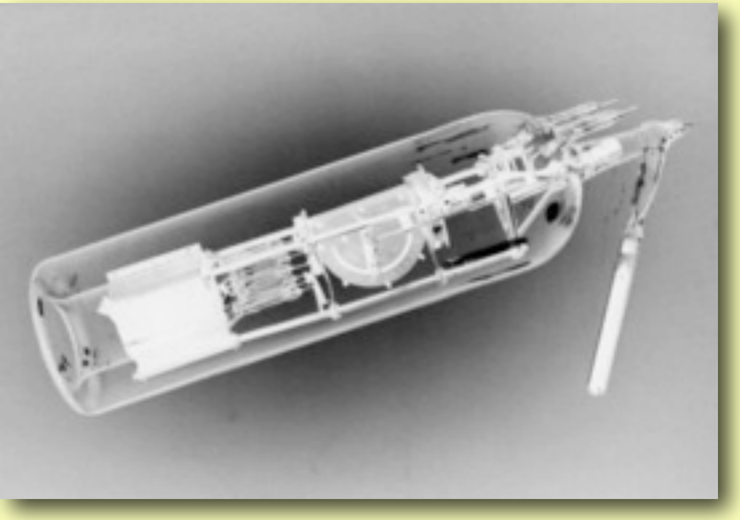
Clinton Davisson
and
Lester Germer



SCATTERING OF 75 VOLT ELECTRONS FROM
A BLOCK OF NICKEL (MANY SMALL CRYSTALS)



SCATTERING OF 75 VOLT ELECTRONS FROM
SEVERAL LARGE NICKEL CRYSTALS



Electron diffraction observed
by reflection from nickel crystals (1927)

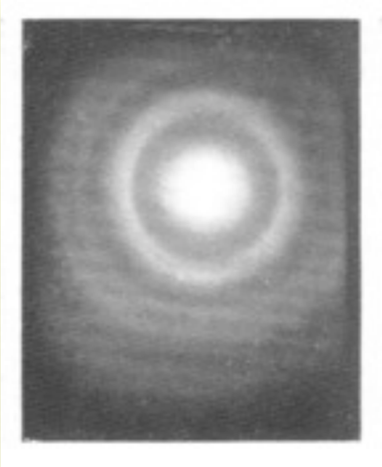
”The investigation reported in this paper was begun as the result of an accident which occured in this laboratory in April 1925. At that time we were continuing an investigation, first reported in 1921 [Davisson & Kunsman, *Science* 64, 522 (1921)], of the distribution-in-angle of electrons scattered by a target of ordinary (polycrystalline) nickel. During the course of this work a liquid-air bottle exploded at a time when the target was at a high temperature; the experimental tube was broken, and the target heavily oxidized by the inrushing air. The oxide was eventually reduced and a layer of the target removed by vaporization, but only after prolonged heating at various temperatures in hydrogen and vacuum.

When the experiments were continued it was found that the distribution-in-angle of the scattered electrons had been completely changed...

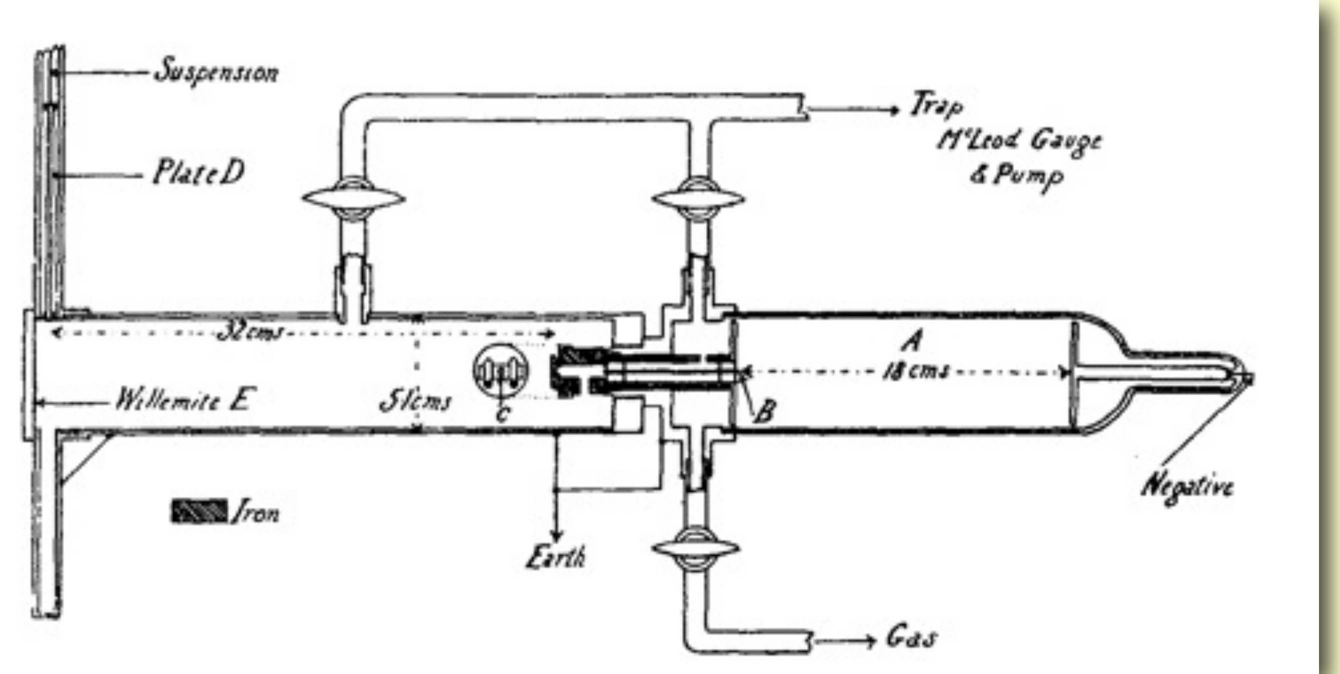
We must admit that the results obtained in these experiments have proved to be quite at variance with our expectations.”

C. Davisson & L. H. Germer, *Phys.Rev.* 30, 705 (1927)

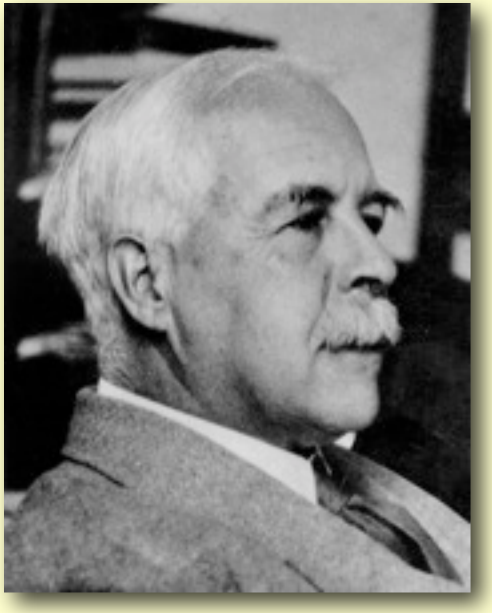
George P. Thomson



Electron diffraction observed in a gold foil



Schematic view of Thomson’s apparatus



Gilbert Newton Lewis

”It would seem inappropriate to speak of one of these hypothetical entities as a particle of light, a corpuscle of light, a light quantum, or a light quant, if we are to assume that it spends only a minute fraction of its existence as a carrier of radiant energy, while the rest of the time it remains as an important structural element within the atom. It would also cause confusion to call it merely a quantum, for later it will be necessary to distinguish between the number of these entities present in an atom and the so-called quantum number. **I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name *photon*.**”

Letter to *Nature*, **118**, 784 (1926)

Important dates in the development of quantum mechanics

1923 IX	Wave nature of electrons (De Broglie)
1924 I	Theory of radiation by Bohr, Kramers, and Slater
1924 VII	Quantum statistics (Bose and Einstein)
1925 I	Pauli exclusion principle
1925 VII	Matrix mechanics of Heisenberg
1925 X	Electron spin (Goudsmit, Uhlenbeck)
1925 XI	Paper by Born, Heisenberg, and Jordan (*Dreimännerarbeit*)
1925 XI	Quantum mechanics of Dirac
1926 I	Hydrogen atom in matrix mechanics (Pauli, Dirac)
1926 I	Wave mechanics of Schrödinger
1926 II	Quantum statistics (Fermi)
1926 VI	Probabilistic interpretation of the wave function (Born)
1926 VIII	Quantum statistics (Dirac)
1927 III	Uncertainty principle (Heisenberg)
1927	Diffraction of electrons (Davisson & Germer, G. Thomson)
1928 I	Quantum theory of electrons (Dirac)

The founders of quantum mechanics

Louis Victor
de Broglie
(1892-1987)

Werner
Heisenberg
(1901-1976)

Erwin
Schrödinger
(1887-1961)

Pascual
Jordan
(1902-1980)

Max
Born
(1882-1970)

Wolfgang
Pauli
(1900-1958)

Paul Adrien
Dirac
(1902-1984)

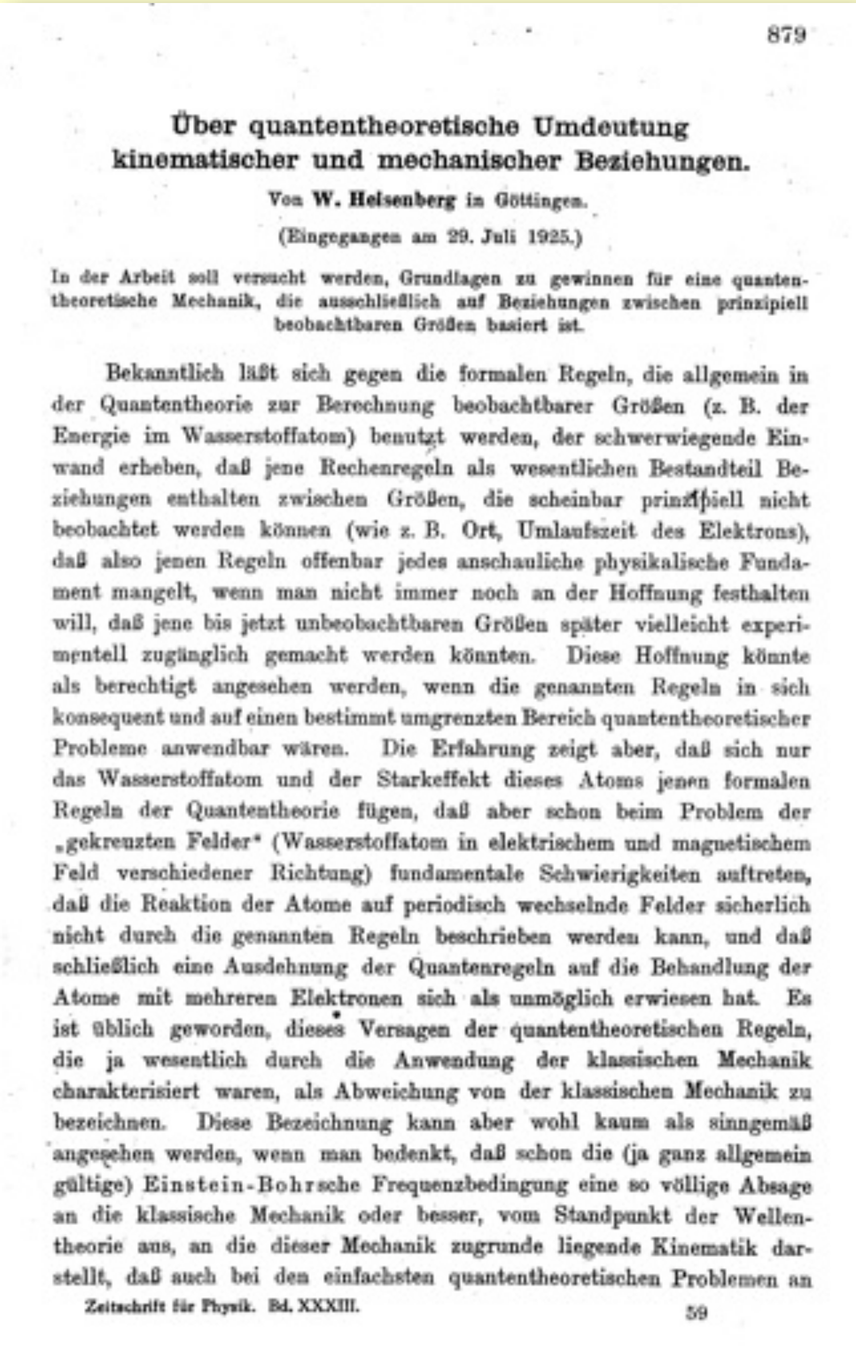
Niels Hendrik
Bohr
(1885-1962)

Heisenberg to Pauli (July 9, 1925)

”It is really my conviction that an interpretation of the Rydberg formula [e.g. for hydrogen] in terms of circular and elliptical orbits (according to *classical* geometry) does not have the slightest physical significance. And all my whole wretched efforts are devoted to killing totally the concept of an orbit - which one cannot observe anyway - and replace it by a more suitable one.”

The birth of quantum mechanics

Werner Heisenberg
(photo ca. 1924)



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Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen.

Von **W. Heisenberg** in Göttingen.

(Eingegangen am 29. Juli 1925.)

In der Arbeit soll versucht werden, Grundlagen zu gewinnen für eine quantentheoretische Mechanik, die ausschließlich auf Beziehungen zwischen prinzipiell beobachtbaren Größen basiert ist.

Bekanntlich läßt sich gegen die formalen Regeln, die allgemein in der Quantentheorie zur Berechnung beobachtbarer Größen (z. B. der Energie im Wasserstoffatom) benutzt werden, der schwerwiegende Einwand erheben, daß jene Rechenregeln als wesentlichen Bestandteil Beziehungen enthalten zwischen Größen, die scheinbar prinzipiell nicht beobachtet werden können (wie z. B. Ort, Umlaufszeit des Elektrons), daß also jenen Regeln offenbar jedes anschauliche physikalische Fundament mangelt, wenn man nicht immer noch an der Hoffnung festhalten will, daß jene bis jetzt unbeobachtbaren Größen später vielleicht experimentell zugänglich gemacht werden könnten. Diese Hoffnung könnte als berechtigt angesehen werden, wenn die genannten Regeln in sich konsequent und auf einen bestimmt umgrenzten Bereich quantentheoretischer Probleme anwendbar wären. Die Erfahrung zeigt aber, daß sich nur das Wasserstoffatom und der Starkeffekt dieses Atoms jenen formalen Regeln der Quantentheorie fügen, daß aber schon beim Problem der „gekreuzten Felder“ (Wasserstoffatom in elektrischem und magnetischem Feld verschiedener Richtung) fundamentale Schwierigkeiten auftreten, daß die Reaktion der Atome auf periodisch wechselnde Felder sicherlich nicht durch die genannten Regeln beschrieben werden kann, und daß schließlich eine Ausdehnung der Quantenregeln auf die Behandlung der Atome mit mehreren Elektronen sich als unmöglich erwiesen hat. Es ist üblich geworden, dieses Versagen der quantentheoretischen Regeln, die ja wesentlich durch die Anwendung der klassischen Mechanik charakterisiert waren, als Abweichung von der klassischen Mechanik zu bezeichnen. Diese Bezeichnung kann aber wohl kaum als sinngemäß angesehen werden, wenn man bedenkt, daß schon die (ja ganz allgemein gültige) Einstein-Bohrsche Frequenzbedingung eine so völlige Absage an die klassische Mechanik oder besser, vom Standpunkt der Wellentheorie aus, an die dieser Mechanik zugrunde liegende Kinematik darstellt, daß auch bei den einfachsten quantentheoretischen Problemen an

Zeitschrift für Physik. Bd. XXXIII. 59

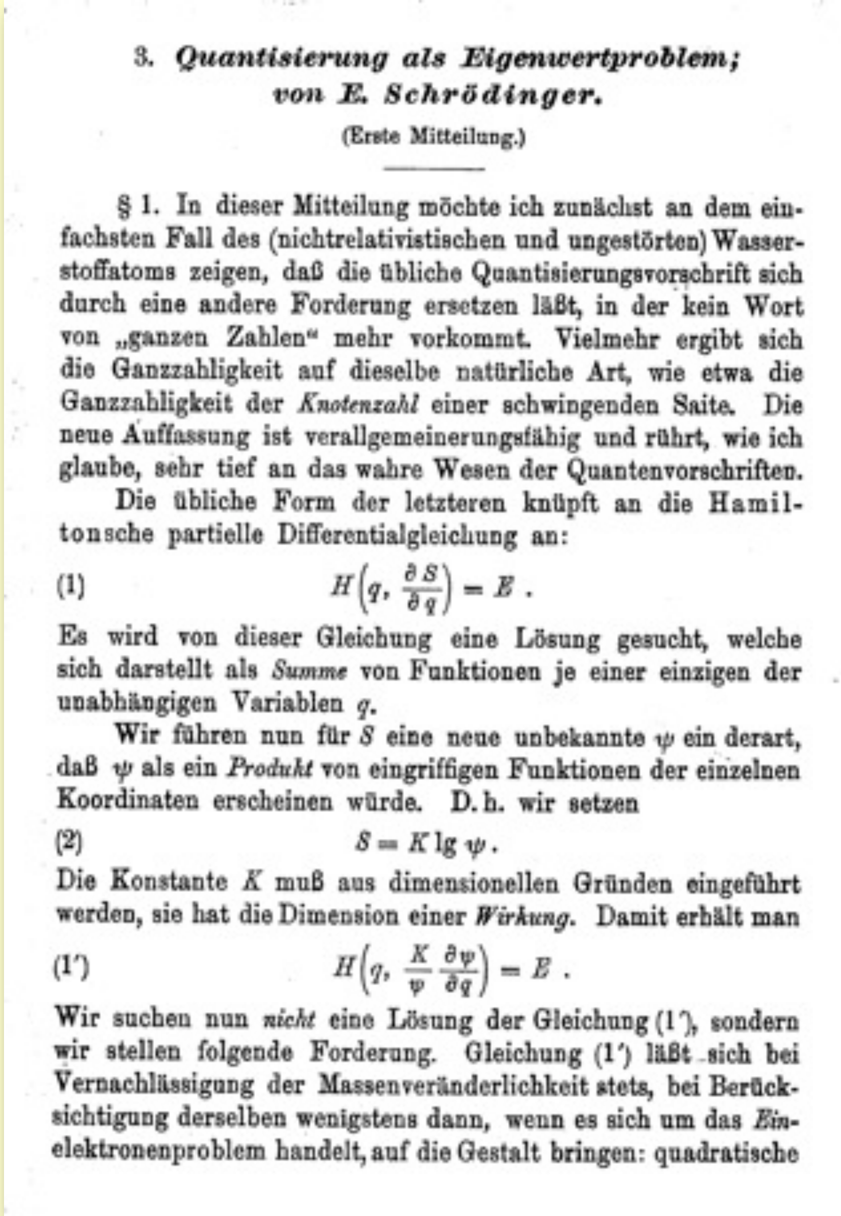
”It is well known that the formal rules which are used in quantum theory for calculating observable quantities (such as the energy of the hydrogen atom) may be seriously criticized on the grounds that they contain, as an essential element, relationships between quantities that are apparently unobservable in principle (such as position, period of revolution of the electron etc.); that these rules lack an evident physical foundation, unless one still retains the hope that the hitherto unobservable quantities may perhaps later become accessible to experimental determination...”

”...Instead it seems more reasonable to try to establish a theoretical quantum mechanics, analogous to classical mechanics, but in which only relations between observable quantities occur.”

Werner Heisenberg, *Z.Phys.* **33**, 879 (1925)

The birth of wave mechanics

Ann. d. Physik **79**, 301 (1926)



3. *Quantisierung als Eigenwertproblem;*
von E. Schrödinger.

(Erste Mitteilung.)

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§ 1. In dieser Mitteilung möchte ich zunächst an dem einfachsten Fall des (nichtrelativistischen und ungestörten) Wasserstoffatoms zeigen, daß die übliche Quantisierungsvorschrift sich durch eine andere Forderung ersetzen läßt, in der kein Wort von „ganzen Zahlen" mehr vorkommt. Vielmehr ergibt sich die Ganzzahligkeit auf dieselbe natürliche Art, wie etwa die Ganzzahligkeit der *Knotenzahl* einer schwingenden Saite. Die neue Auffassung ist verallgemeinerungsfähig und rührt, wie ich glaube, sehr tief an das wahre Wesen der Quantenvorschriften.

Die übliche Form der letzteren knüpft an die Hamiltonsche partielle Differentialgleichung an:

(1) $$H\left(q, \frac{\partial S}{\partial q}\right) = E .$$

Es wird von dieser Gleichung eine Lösung gesucht, welche sich darstellt als *Summe* von Funktionen je einer einzigen der unabhängigen Variablen q.

Wir führen nun für S eine neue unbekannte ψ ein derart, daß ψ als ein *Produkt* von eingriffigen Funktionen der einzelnen Koordinaten erscheinen würde. D. h. wir setzen

(2) $$S = K \lg \psi .$$

Die Konstante K muß aus dimensionellen Gründen eingeführt werden, sie hat die Dimension einer *Wirkung*. Damit erhält man

(1') $$H\left(q, \frac{K}{\psi}\frac{\partial \psi}{\partial q}\right) = E .$$

Wir suchen nun *nicht* eine Lösung der Gleichung (1'), sondern wir stellen folgende Forderung. Gleichung (1') läßt sich bei Vernachlässigung der Massenveränderlichkeit stets, bei Berücksichtigung derselben wenigstens dann, wenn es sich um das *Einelektronenproblem* handelt, auf die Gestalt bringen: quadratische

Erwin Schrödinger

”In this communication I wish first to show in the simplest case of the hydrogen atom (nonrelativistic and undistorted) that the usual rules for quantization can be replaced by another requirement, in which mention of ‘whole numbers’ no longer occurs. Instead the integers occur in the same natural way as the integers specifying the number of nodes in a vibrating string. The new conception can be generalized, and I believe it touches the deepest meaning of the quantum rules.”

Ann. d. Physik **79**, 301 (1926)

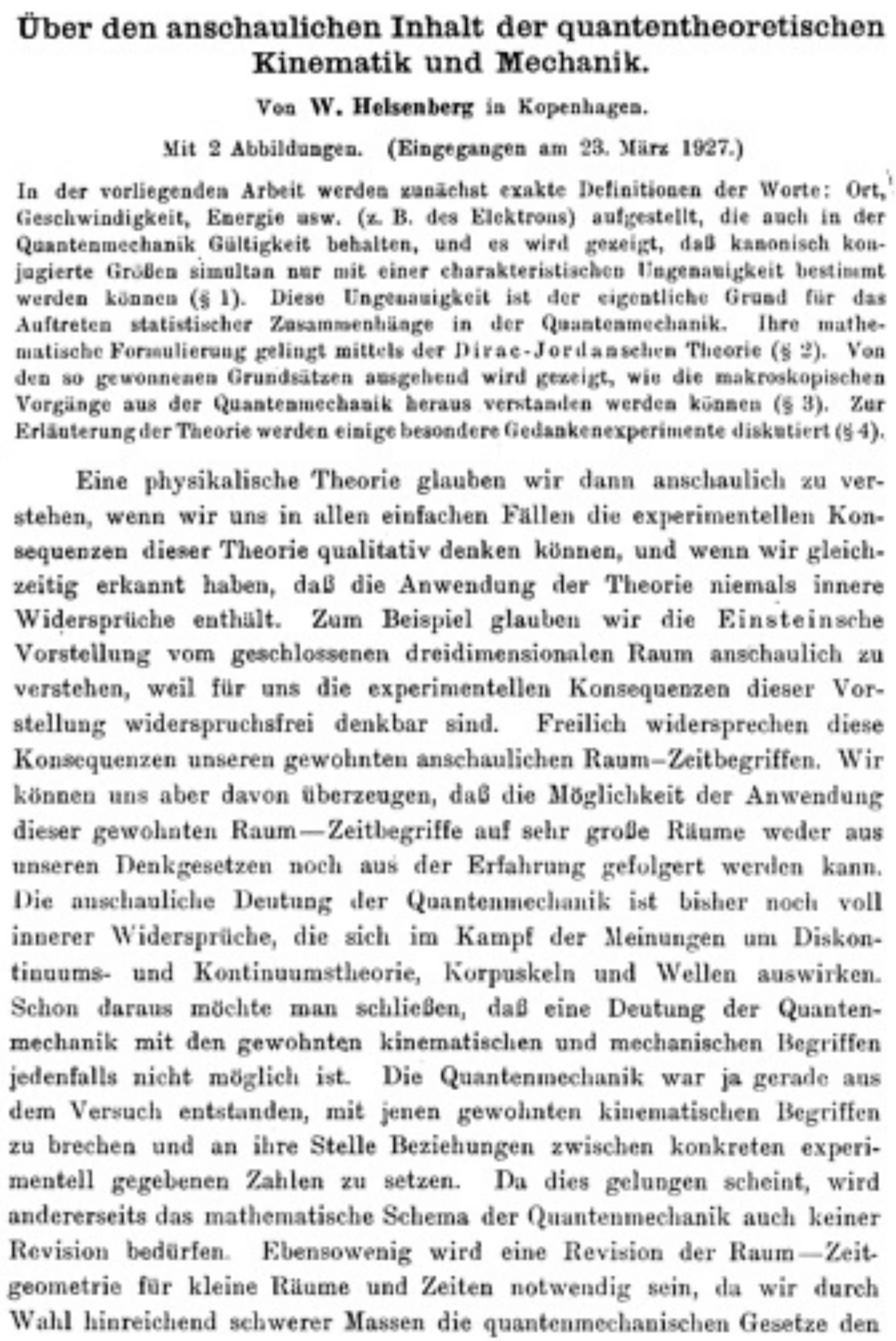
Schrödinger about Heisenberg’s matrix mechanics (1926)

"My theory was inspired by L. de Broglie and by brief but infinitely far-seeing remarks of A. Einstein [Berl. Ber. 1925, p.9ff]. I was absolutely unaware of any genetic relationship with Heisenberg. I naturally knew about his theory, but because of the to me very difficult-appearing methods of transcendental algebra and because of the lack of visualibility (*Anschaulichkeit*), I felt deterred by it, if not to say repelled."

Heisenberg about Schrödinger’s wave mechanics (1926)

"The more I think of the physical part of the Schrödinger theory, the more abominable I find it. What Schrödinger writes about *Anschaulichkeit* makes scarcely any sense, in other words I think it is bullshit (*Mist)*."

The uncertainty principle



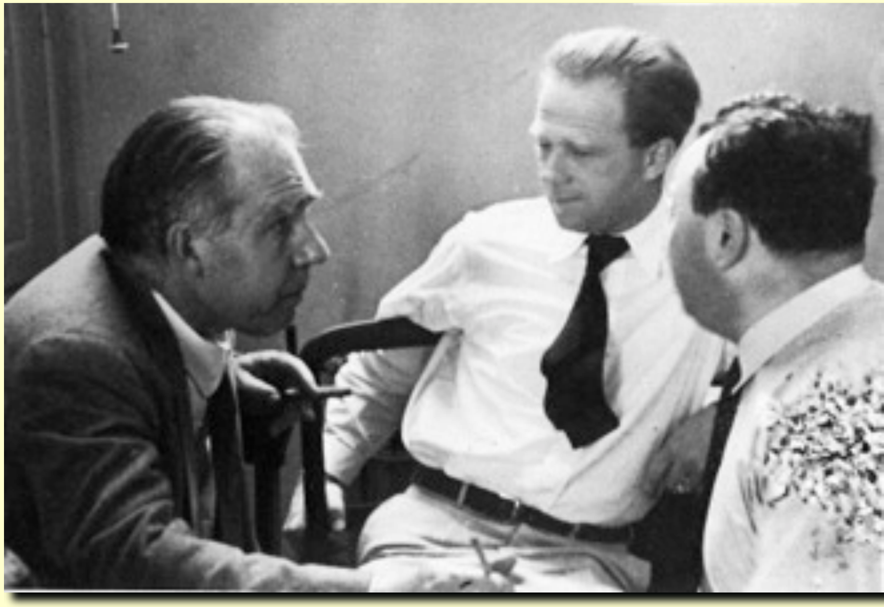
Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik.

Von **W. Heisenberg** in Kopenhagen.

Mit 2 Abbildungen. (Eingegangen am 23. März 1927.)

In der vorliegenden Arbeit werden zunächst exakte Definitionen der Worte: Ort, Geschwindigkeit, Energie usw. (z. B. des Elektrons) aufgestellt, die auch in der Quantenmechanik Gültigkeit behalten, und es wird gezeigt, daß kanonisch konjugierte Größen simultan nur mit einer charakteristischen Ungenauigkeit bestimmt werden können (§ 1). Diese Ungenauigkeit ist der eigentliche Grund für das Auftreten statistischer Zusammenhänge in der Quantenmechanik. Ihre mathematische Formulierung gelingt mittels der Dirac-Jordanschen Theorie (§ 2). Von den so gewonnenen Grundsätzen ausgehend wird gezeigt, wie die makroskopischen Vorgänge aus der Quantenmechanik heraus verstanden werden können (§ 3). Zur Erläuterung der Theorie werden einige besondere Gedankenexperimente diskutiert (§ 4).

Eine physikalische Theorie glauben wir dann anschaulich zu verstehen, wenn wir uns in allen einfachen Fällen die experimentellen Konsequenzen dieser Theorie qualitativ denken können, und wenn wir gleichzeitig erkannt haben, daß die Anwendung der Theorie niemals innere Widersprüche enthält. Zum Beispiel glauben wir die Einsteinsche Vorstellung vom geschlossenen dreidimensionalen Raum anschaulich zu verstehen, weil für uns die experimentellen Konsequenzen dieser Vorstellung widerspruchsfrei denkbar sind. Freilich widersprechen diese Konsequenzen unseren gewohnten anschaulichen Raum–Zeitbegriffen. Wir können uns aber davon überzeugen, daß die Möglichkeit der Anwendung dieser gewohnten Raum—Zeitbegriffe auf sehr große Räume weder aus unseren Denkgesetzen noch aus der Erfahrung gefolgert werden kann. Die anschauliche Deutung der Quantenmechanik ist bisher noch voll innerer Widersprüche, die sich im Kampf der Meinungen um Diskontinuums- und Kontinuumstheorie, Korpuskeln und Wellen auswirken. Schon daraus möchte man schließen, daß eine Deutung der Quantenmechanik mit den gewohnten kinematischen und mechanischen Begriffen jedenfalls nicht möglich ist. Die Quantenmechanik war ja gerade aus dem Versuch entstanden, mit jenen gewohnten kinematischen Begriffen zu brechen und an ihre Stelle Beziehungen zwischen konkreten experimentell gegebenen Zahlen zu setzen. Da dies gelungen scheint, wird andererseits das mathematische Schema der Quantenmechanik auch keiner Revision bedürfen. Ebensowenig wird eine Revision der Raum—Zeitgeometrie für kleine Räume und Zeiten notwendig sein, da wir durch Wahl hinreichend schwerer Massen die quantenmechanischen Gesetze den



”I used to take long walks on Sundays alone, thinking about these problems and it was during one such walk that the idea occurred to me that the commutator *A* times *B* minus *B* times *A* was very similar to the Poisson bracket which one has in classical mechanics when one formulates the equations in the Hamiltonian form. That was an idea that I just jumped at as soon as it occurred to me. But then I was held back by the fact that I did not know very well what was a Poisson bracket. It was something which I had read about in advanced books of dynamics, but there was not really very much use for it, and after reading about it, it had slipped our of my mind and I did not very well remember what the situation was. It became necessary to check whether the Poisson bracket really could be made to correspond to the commutator and I needed to have a precise definition of the Poisson bracket.”

Paul Dirac

”Well, I hurried home and looked through all my books and papers and could not find any reference in them to Poisson brackets. The books that I had were all too elementary. It was a Sunday, I could not go to a library then; I just had to wait impatiently through that night and then the next morning early, when the libraries opened, I went and checked what a Poisson bracket really is and found that it was as I had thought and that one could set up the connection between a Poisson bracket and a commutator. This provided a very close connection between the ordinary classical mechanics which people were used to and the new mechanics involving the noncommuting quantities which had been introduced by Heisenberg.
After this early idea, the work was all fairly straightforward. There were really no serious difficulties for quite a long time. One could work out the equations of the new mechanics; one just had to make the appropriate generalization in the classical equations expressed in the Hamiltonian form...”

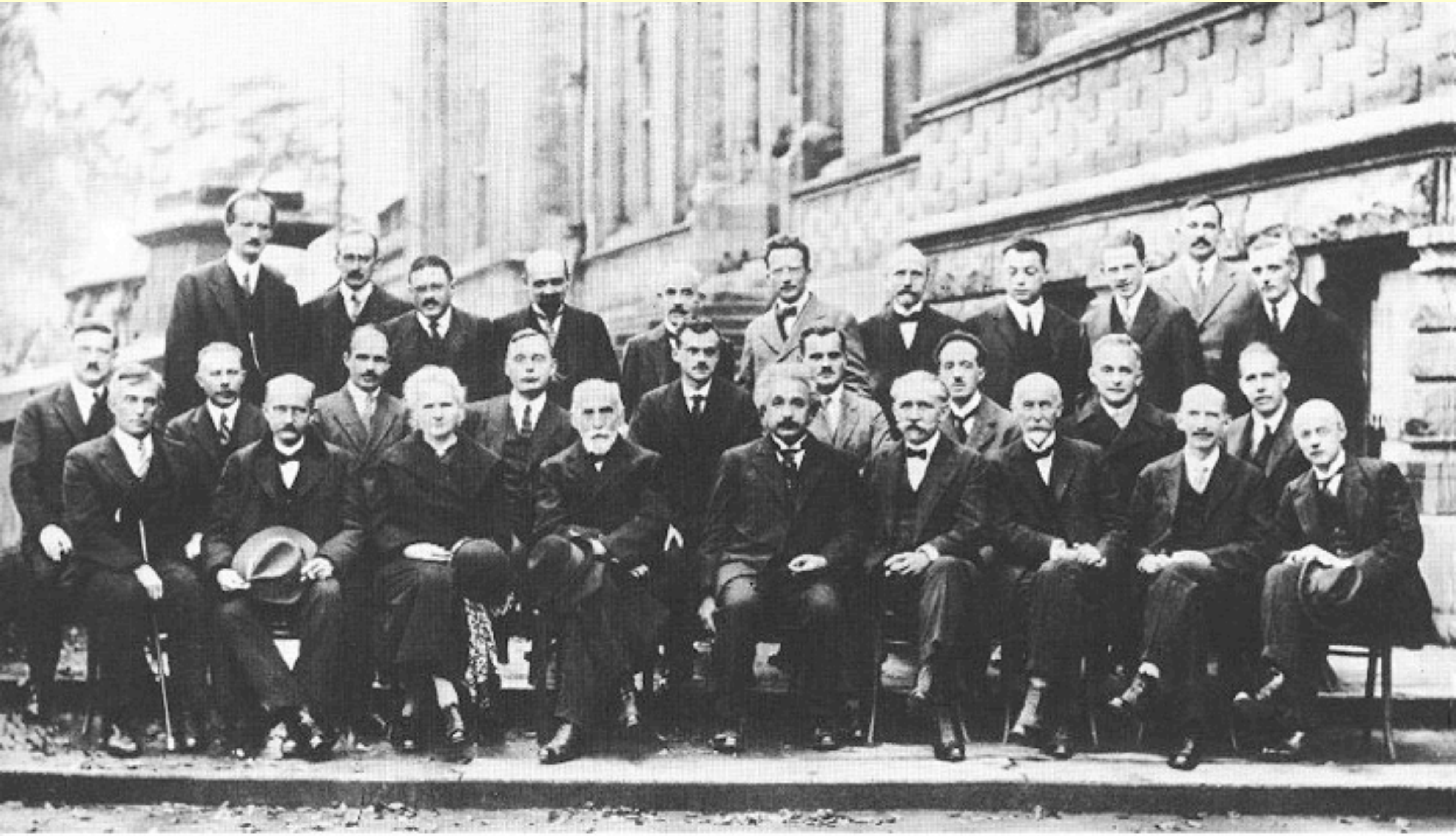
Paul Dirac

”The fact that the variables used for describing a dynamical system do not satisfy the commutative law means, of course, that they are not numbers in the sense of the word previously used in mathematics. To distinguish the two kinds of numbers, we shall call the quantum variables *q*-numbers and the numbers of classical methematics which satisfy the commutative law *c*-numbers, while the word number alone will be used to denote either a *q*-number or a *c*-number. When $xy = yx$ we shall say that x commutes with y. At present one can form no picture of what a *q*-number is like. One cannot say that one *q*-number is greater or less than another. All one knows about q-numbers is that if z_1 and z_2 are two *q*-numbers, or one *q* number and one *c*-number, there exist the numbers $z_1 + z_2$, $z_1 z_2$, $z_2 z_1$, which will in general be *q*-numbers, but may be *c*-numbers. One knows nothing of the processes by which the numbers are formed except that they satisfy all the ordinary laws of algebra, excluding the commutative law of multiplication...”

Dirac (1926)

[Measurements always give *c* numbers]

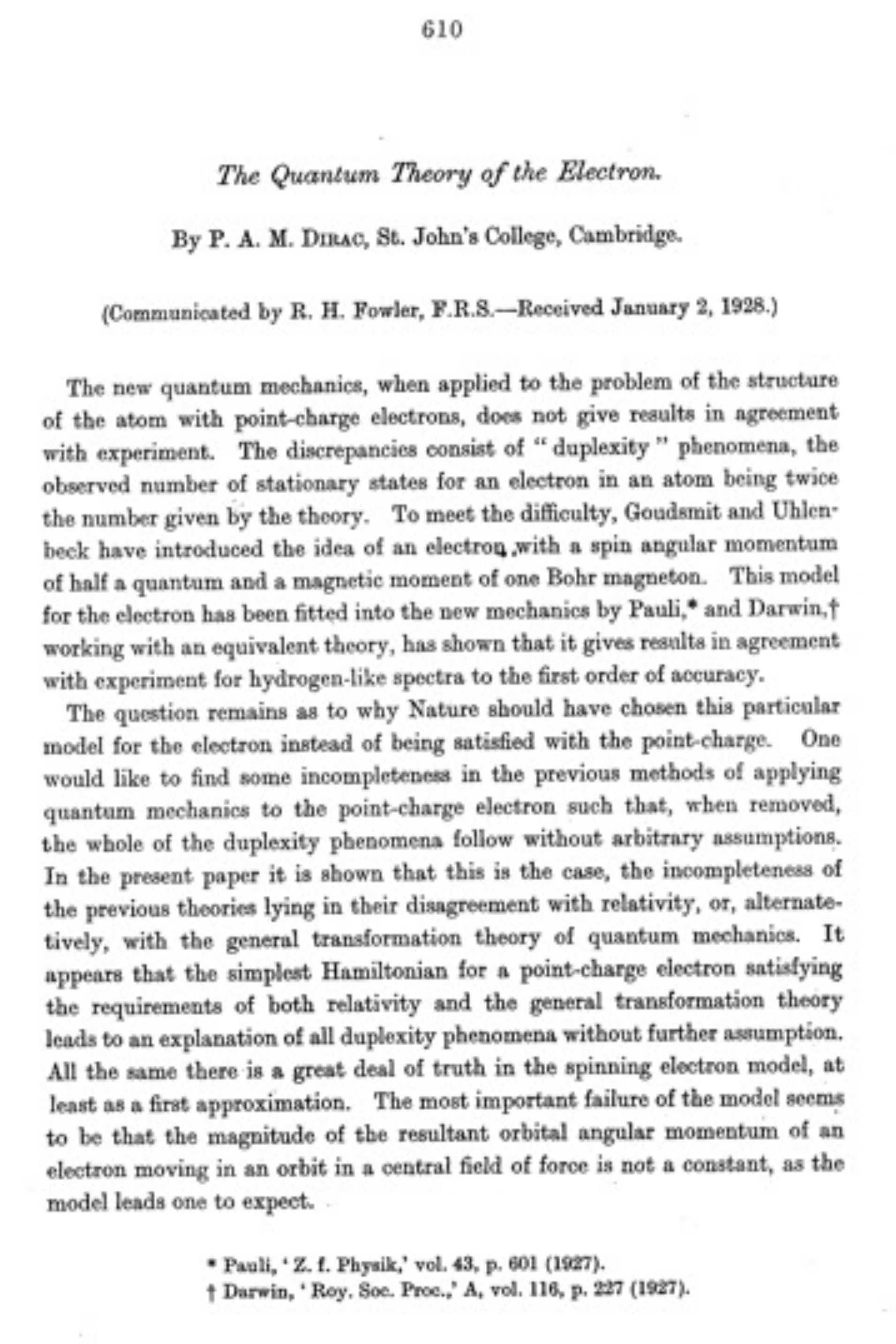
Solvay Conference 1927



A. PICCARD E. HENRIOT P. EHRENFEST Ed. HERZEN Th. DE DONDER E. SCHRÖDINGER 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 Mme CURIE H.A. LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O.W. RICHARDSON



The Quantum Theory of the Electron.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

The new quantum mechanics, when applied to the problem of the structure of the atom with point-charge electrons, does not give results in agreement with experiment. The discrepancies consist of "duplexity" phenomena, the observed number of stationary states for an electron in an atom being twice the number given by the theory. To meet the difficulty, Goudsmit and Uhlenbeck have introduced the idea of an electron with a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton. This model for the electron has been fitted into the new mechanics by Pauli,[*] and Darwin,[†] working with an equivalent theory, has shown that it gives results in agreement with experiment for hydrogen-like spectra to the first order of accuracy.

The question remains as to why Nature should have chosen this particular model for the electron instead of being satisfied with the point-charge. One would like to find some incompleteness in the previous methods of applying quantum mechanics to the point-charge electron such that, when removed, the whole of the duplexity phenomena follow without arbitrary assumptions. In the present paper it is shown that this is the case, the incompleteness of the previous theories lying in their disagreement with relativity, or, alternatetively, with the general transformation theory of quantum mechanics. It appears that the simplest Hamiltonian for a point-charge electron satisfying the requirements of both relativity and the general transformation theory leads to an explanation of all duplexity phenomena without further assumption. All the same there is a great deal of truth in the spinning electron model, at least as a first approximation. The most important failure of the model seems to be that the magnitude of the resultant orbital angular momentum of an electron moving in an orbit in a central field of force is not a constant, as the model leads one to expect.

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[*] Pauli, 'Z. f. Physik,' vol. 43, p. 601 (1927).

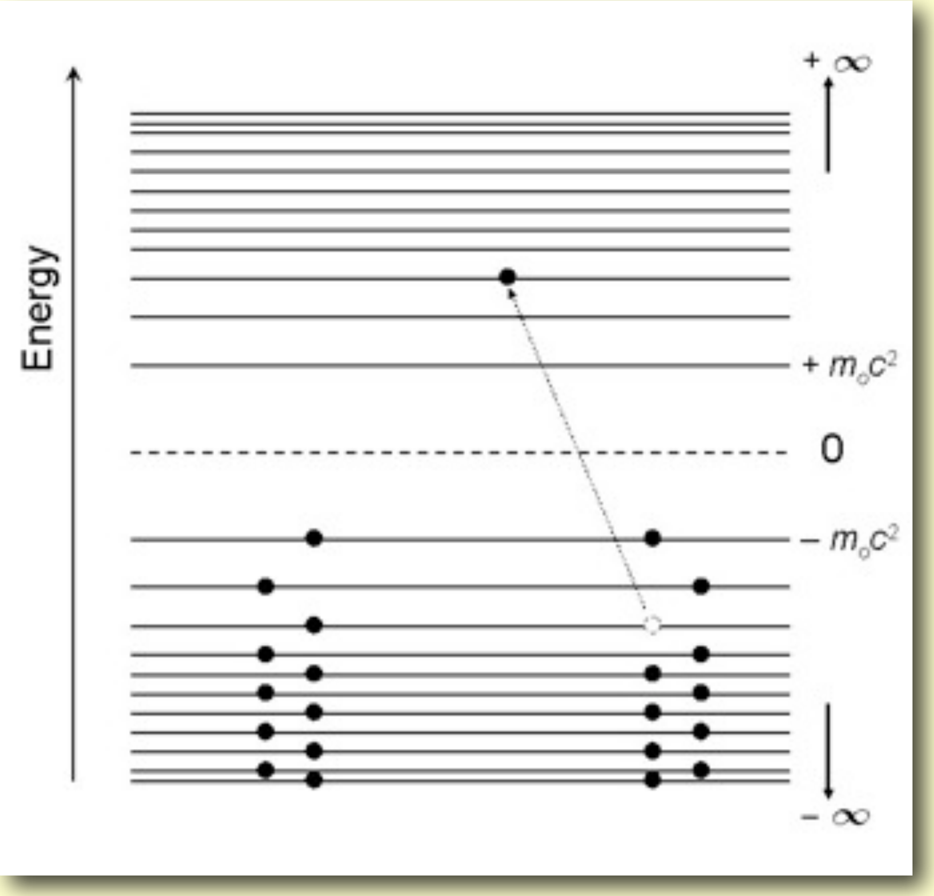
[†] Darwin, 'Roy. Soc. Proc.,' A, vol. 116, p. 227 (1927).

Paul Dirac in 1930

”A recent paper by the author may possibly be regarded as a small step according to this general scheme of advance. The mathematical formalism at that time involved a serious difficulty through its prediction of negative kinetic energy values for an electron. It was proposed to get over this difficulty, making use of Pauli's Exclusion Principle which does not allow more than one electron in any state, by saying that in the physical world almost all the negative-energy states are already occupied, so that our ordinary electrons of positive energy cannot fall into them. The question then arises as to the physical interpretation of the negative-energy states, which on this view really exist. We should expect the uniformly filled distribution of negative-energy states to be completely unobservable to us, but an unoccupied one of these states, being something exceptional, should make its presence felt as a kind of hole. It was shown that one of these holes would appear to us as a particle with a positive energy and a positive charge and it was suggested that this particle should be identified with a proton. Subsequent investigations, however, have shown that this particle necessarily has the same mass as an electron, and also that, if it collides with an electron, the two will have a chance of annihilating one another much too great to be consistent with the known stability of matter.”

Paul Dirac

Dirac’s sea of negative mass electrons



"It thus appears that we must abandon the identification of the holes with protons and must find some other interpretation for them. Following Oppenheimer, we can assume that in the world as we know it, all, and not merely nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of them in nature, on account of their rapid rate of recombination with electrons, but if they could be produced experimentally in high vacuum they would be quite stable and amenable to observation. An encounter between two hard γ-rays (of energy at least half a million volts) could lead to the creation simultaneously of an electron and anti-electron, the probability of occurrence of this process being of the same order of magnitude as that of the collision of the two γ-rays on the assumption that they are spheres of the same size as classical electrons. This probability is negligible, however, with the intensities of γ-rays at present available. The protons on the above view are quite unconnected with electrons. Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton. Theory at present is quite unable to suggest a reason why there should be any differences between electrons and protons...„ Paul Dirac (1931)

”The general theory of quantum mechanics is now almost complete... 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.”

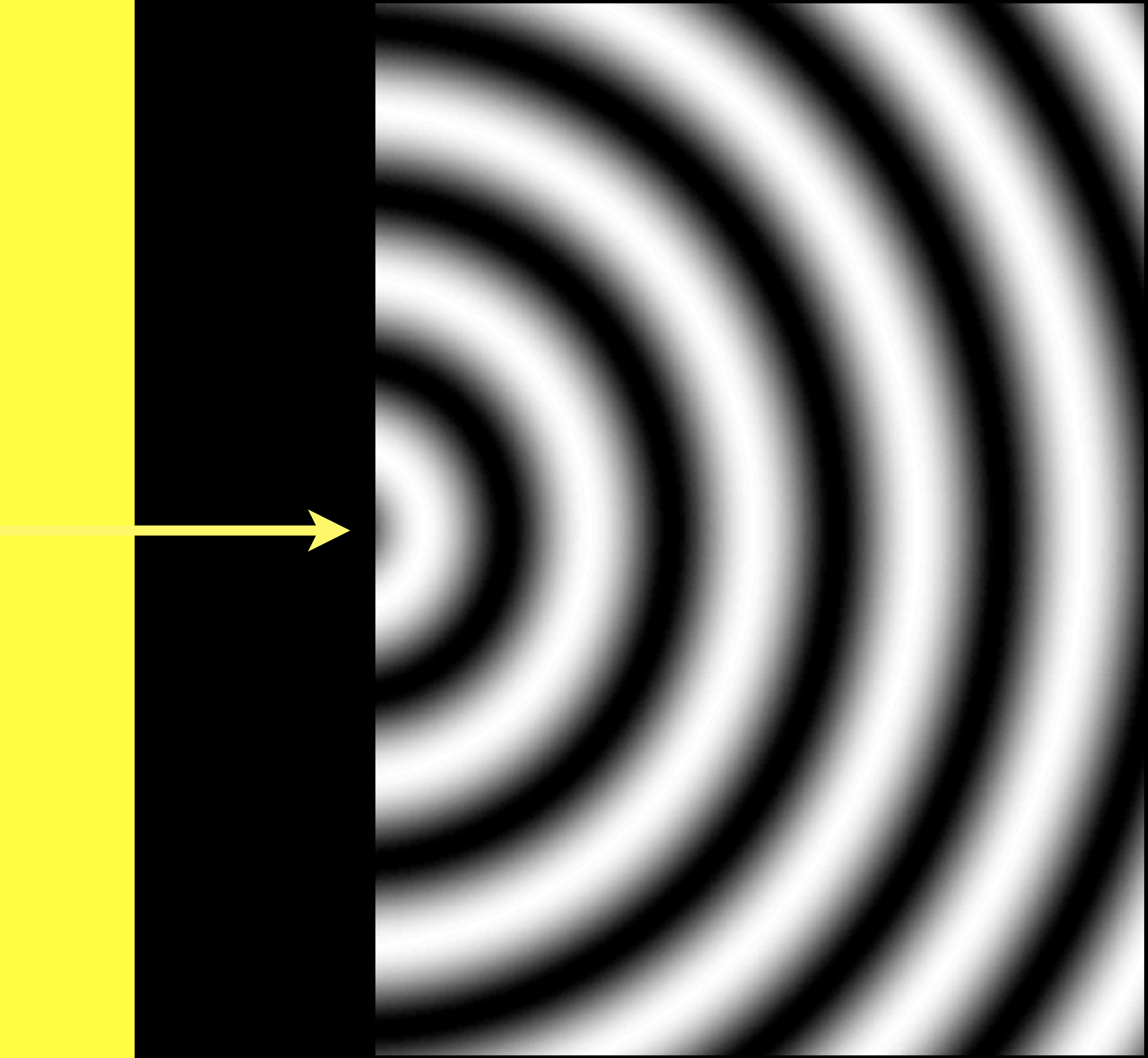
Paul Dirac (1929)

”I think that in six months... physics as we know it will be over”

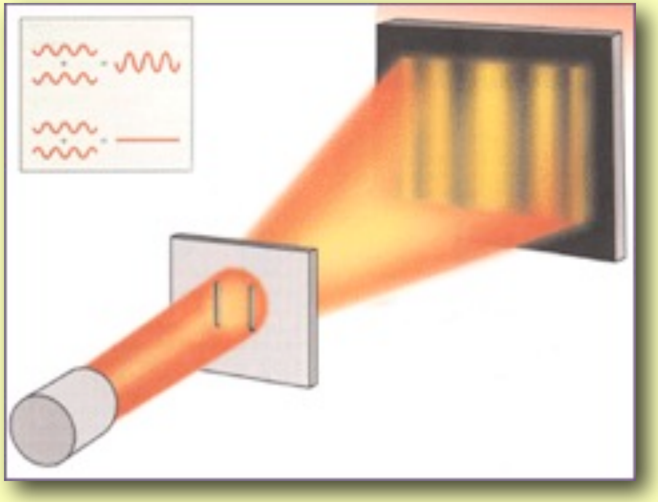
Max Born

(after Dirac’s paper on the relativistic equation of the electron)

Additional explanatory slides

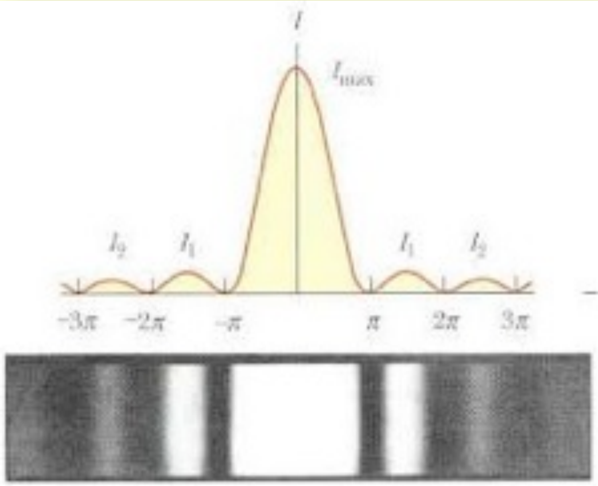


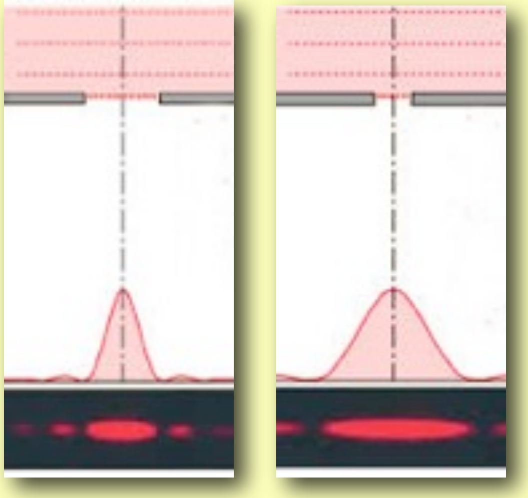
Diffraction of light



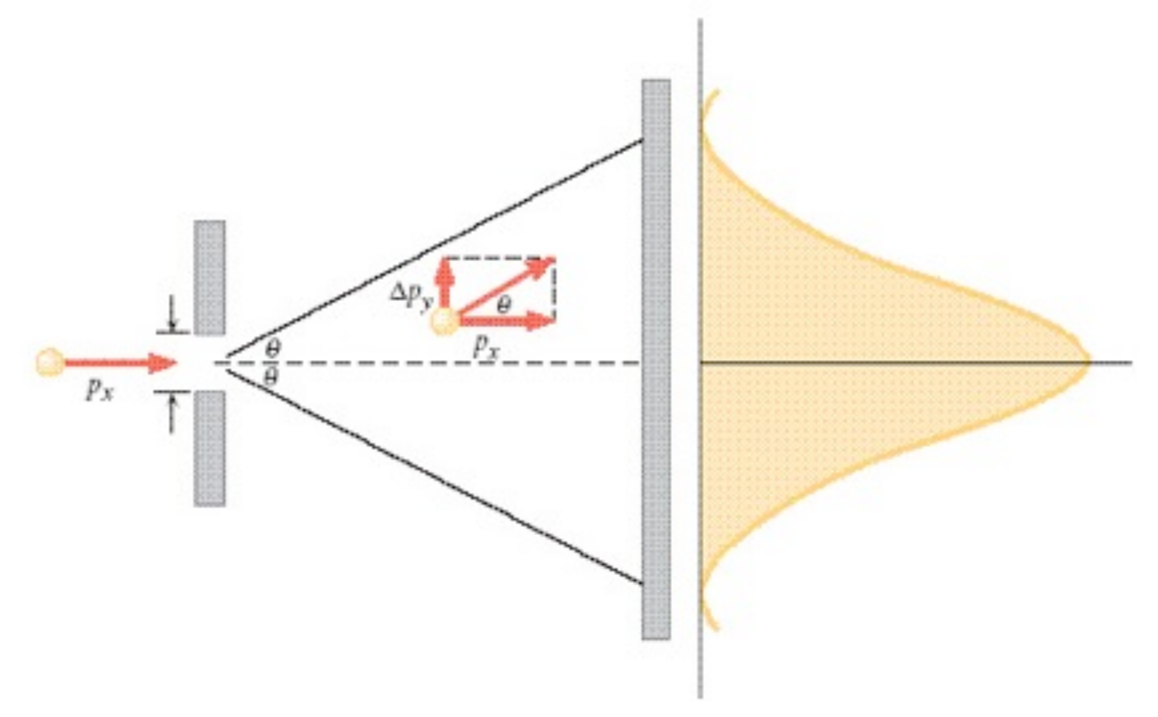
rectangular slit

circular slit

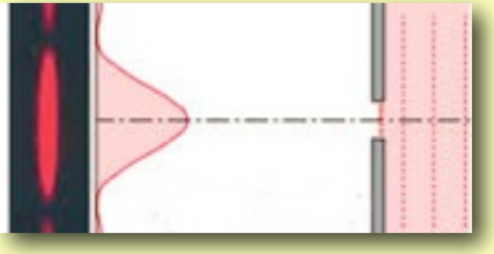


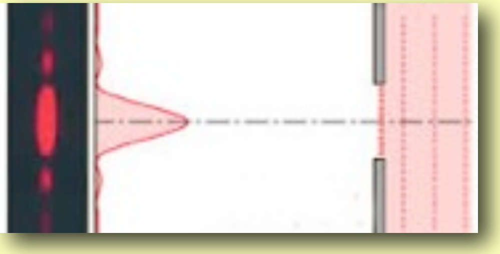


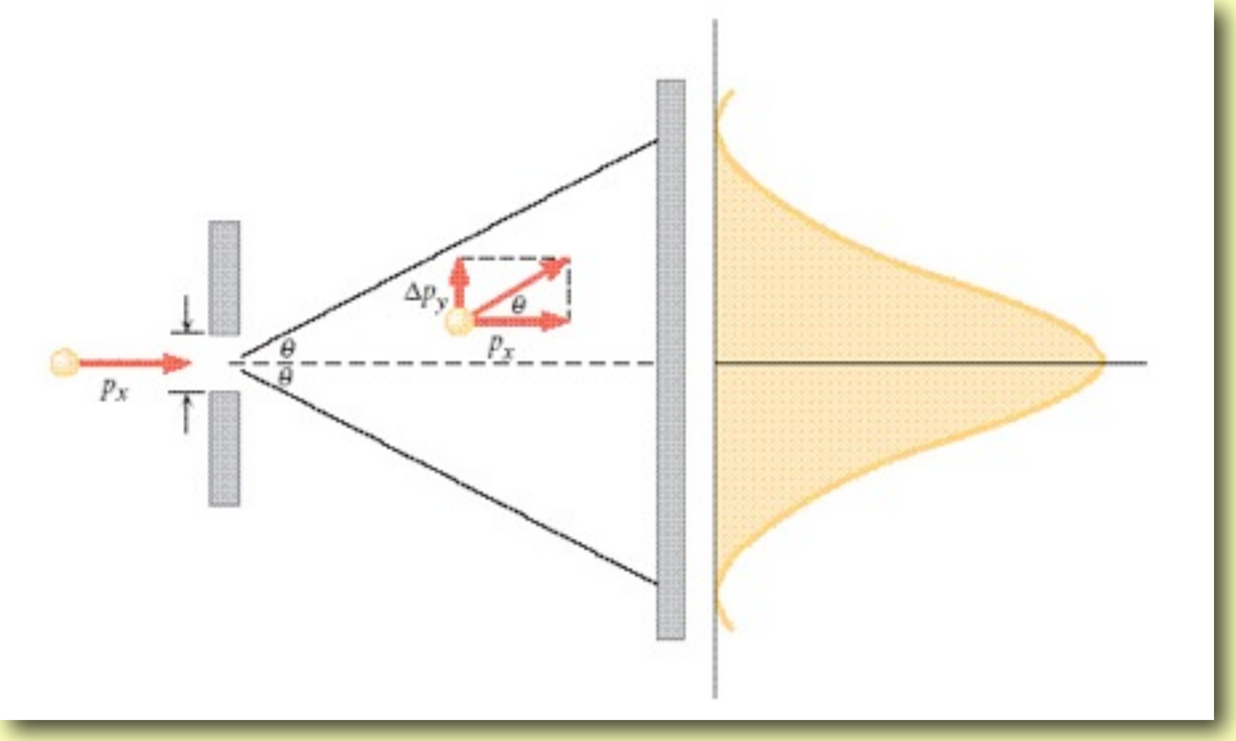
narrower slit provides wider diffraction pattern



$\sin\theta = \lambda/\Delta y$





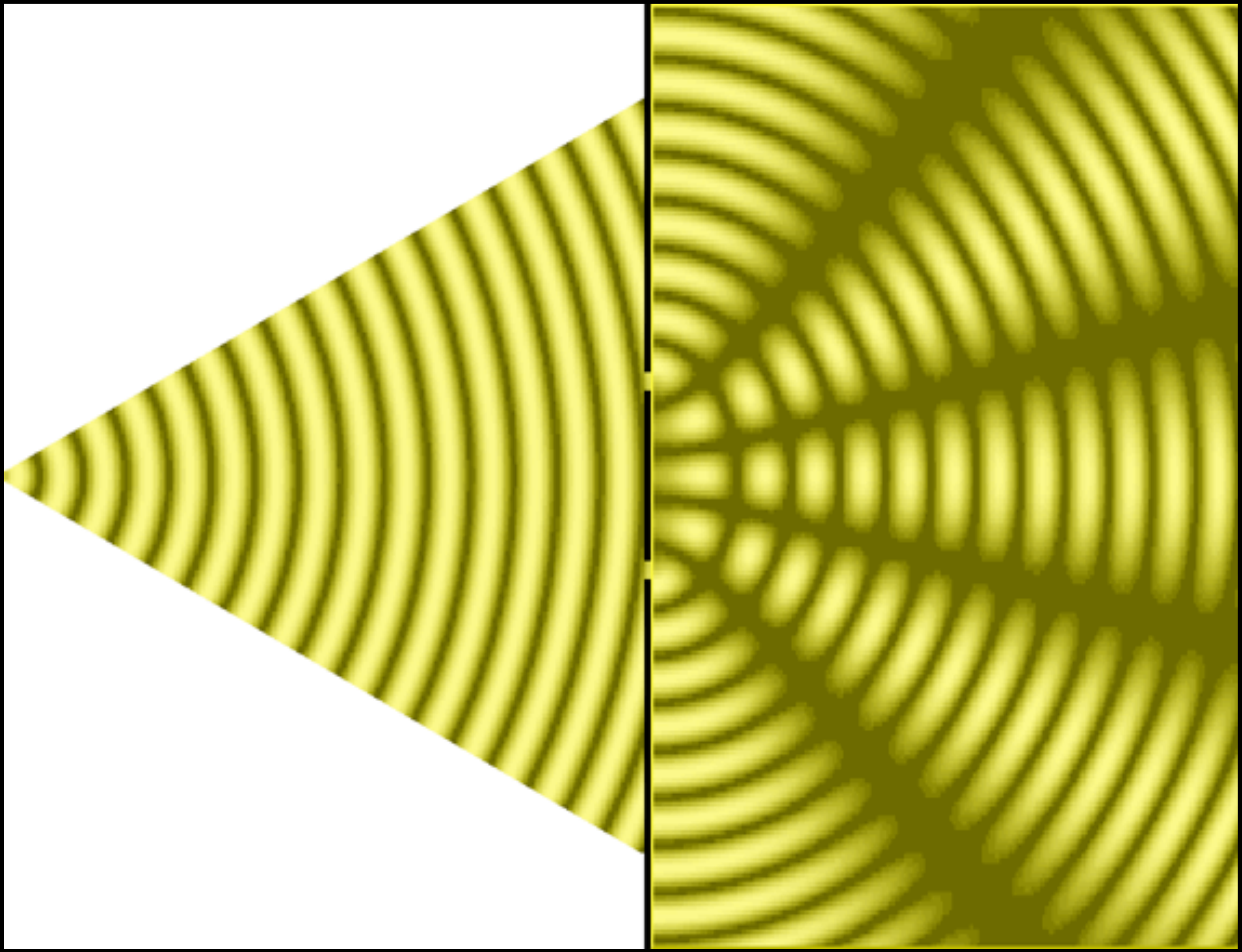


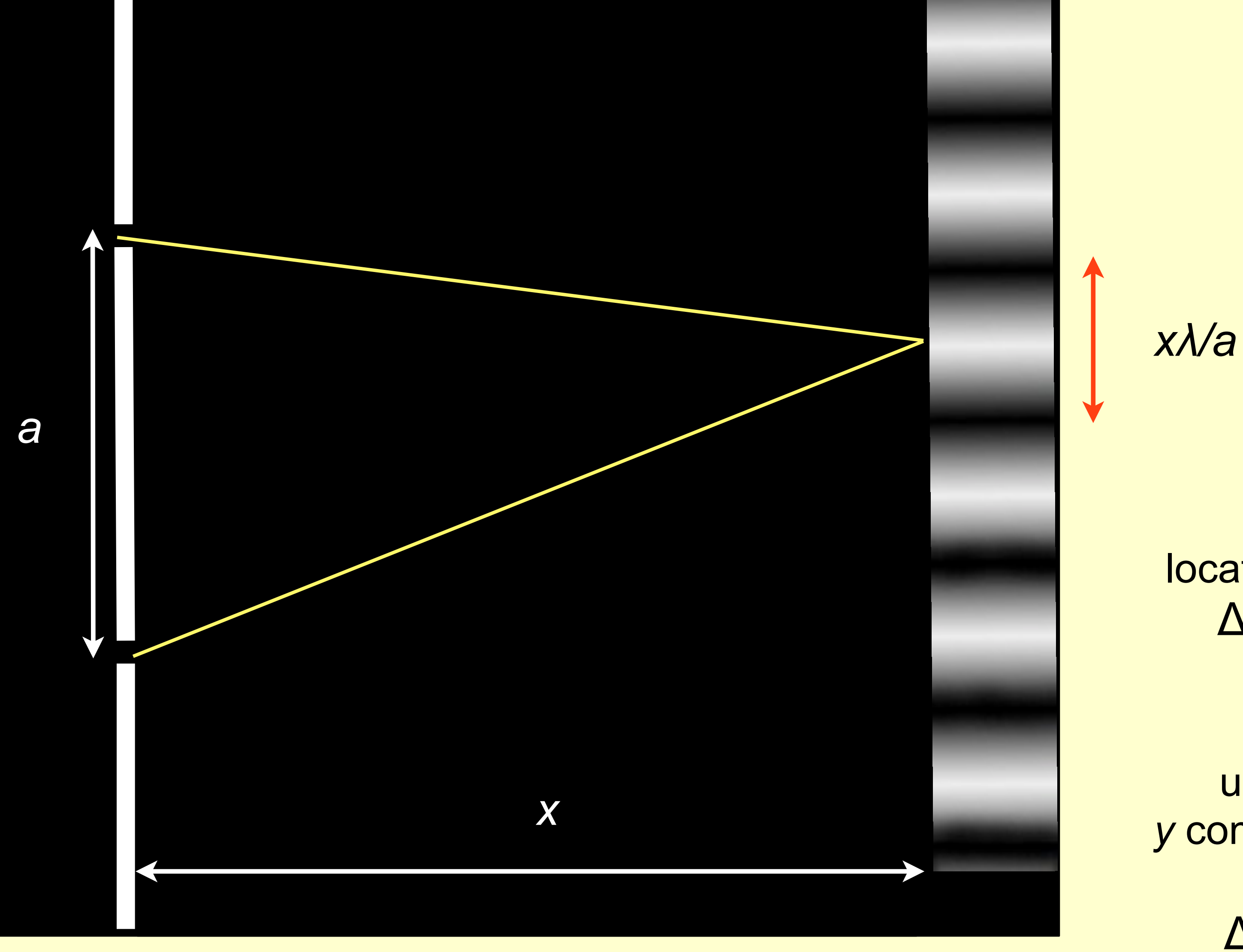
$$\sin\theta = \lambda/\Delta y$$

$$\Delta p_y = p\sin\theta = (h/\lambda)\sin\theta = (h/\lambda)(\lambda/\Delta y) = h/\Delta y$$

$$\Delta p_y \cdot \Delta y \geq h$$

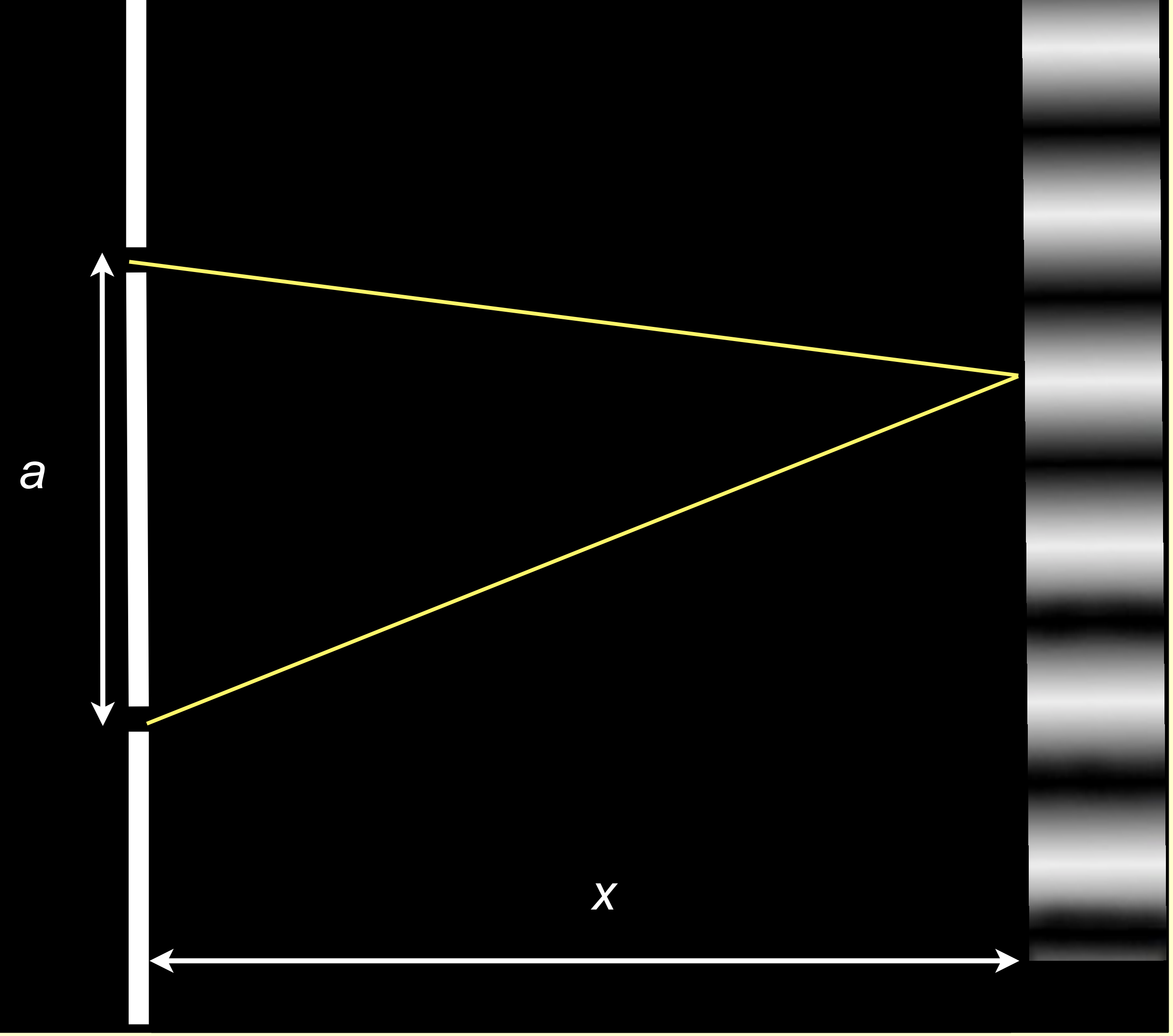
”the uncertainty principle”





location of the photon:
$\Delta y < x\lambda/a = \lambda/\theta$

uncertainty of the
y component of photon’s
momentum:
$\Delta p_y \cong p\theta = h\theta/\lambda$



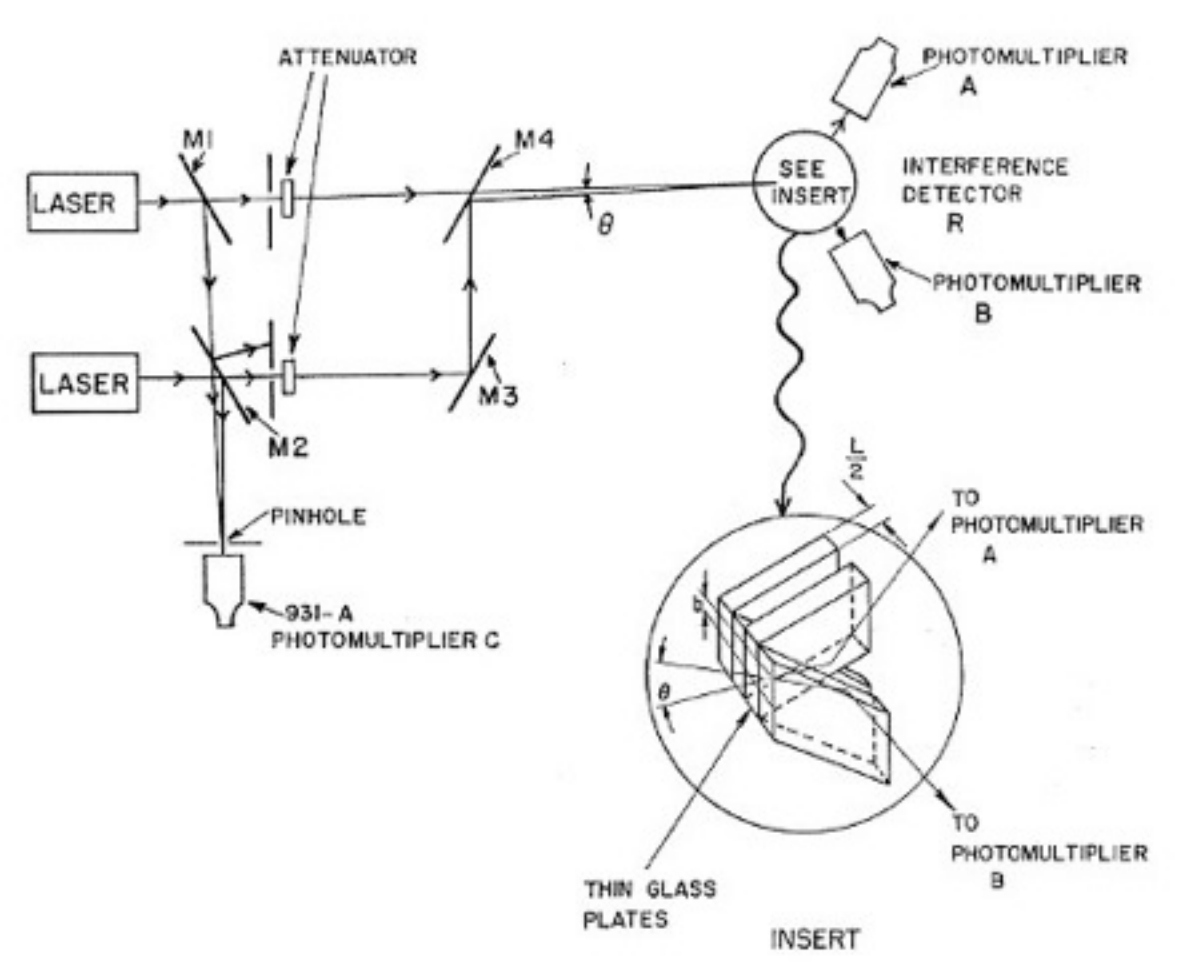
location of the photon:
$\Delta y < x\lambda/a = \lambda/\theta$

uncertainty of the
y component of photon’s
momentum:
$\Delta p_y \cong p\theta = h\theta/\lambda$

$$\boldsymbol{\Delta y \, \Delta p_y \geq h}$$

We are not able to tell from which slit came the photon

„Young's experiment" with two lasers

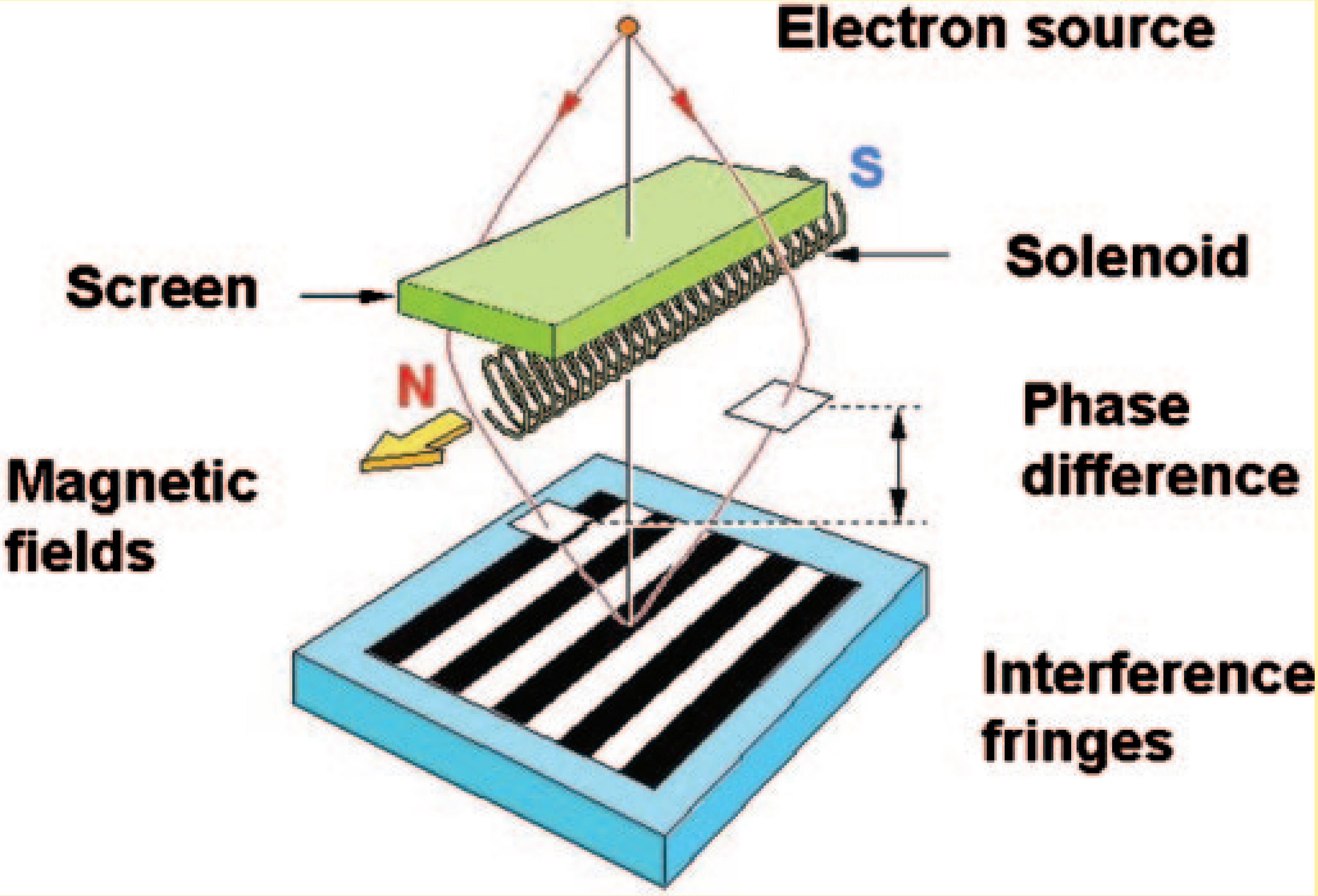


One can't tell from which of the two lasers a photon arrived

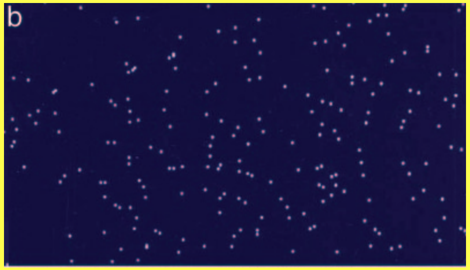
Electrons and other elementary particles, also atoms and molecules, have wave properties

We may observe their diffraction and interference

Diffraction of electrons




a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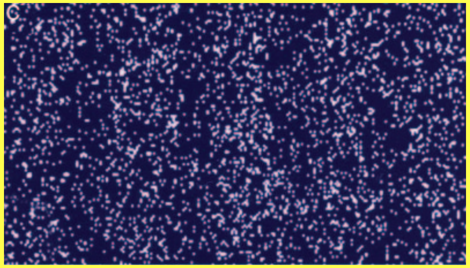
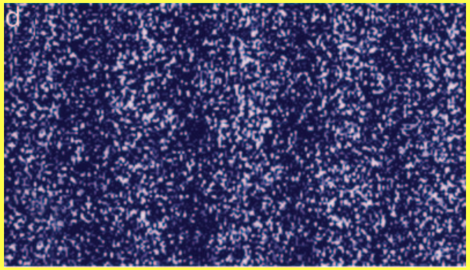

c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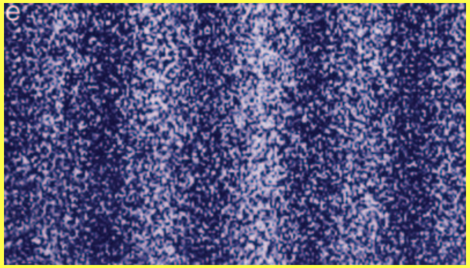
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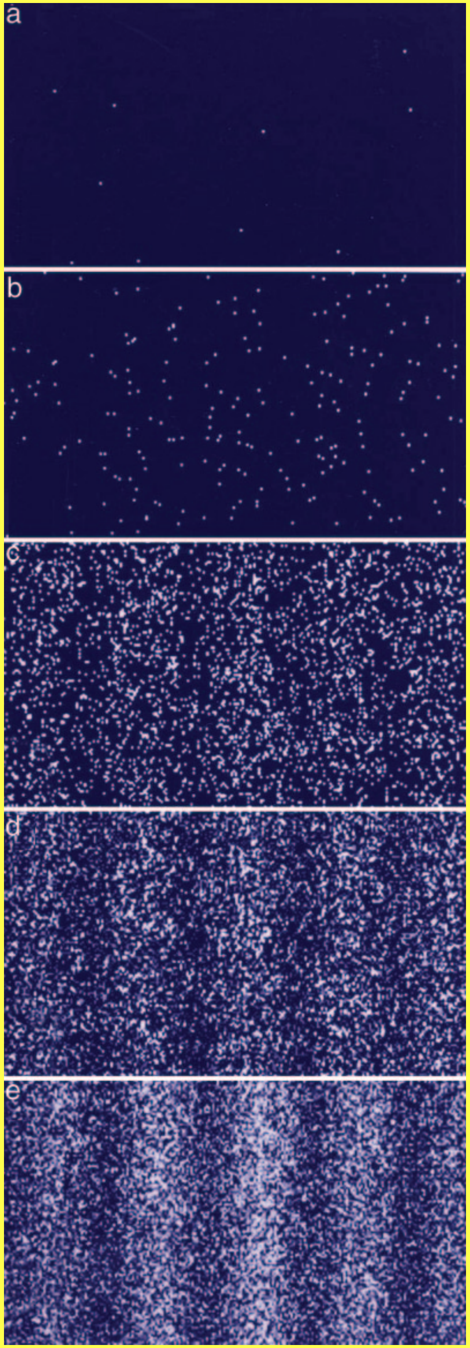
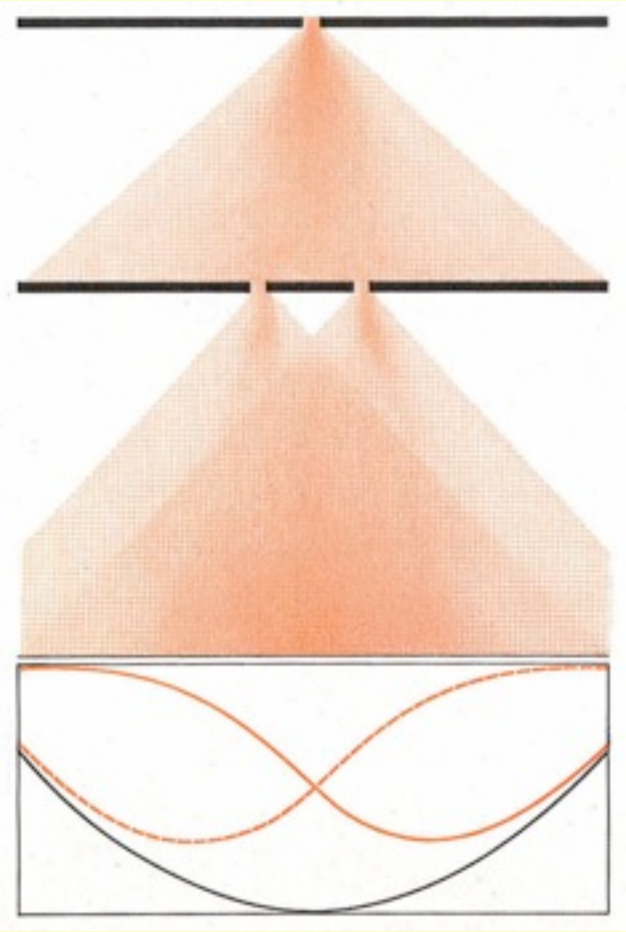
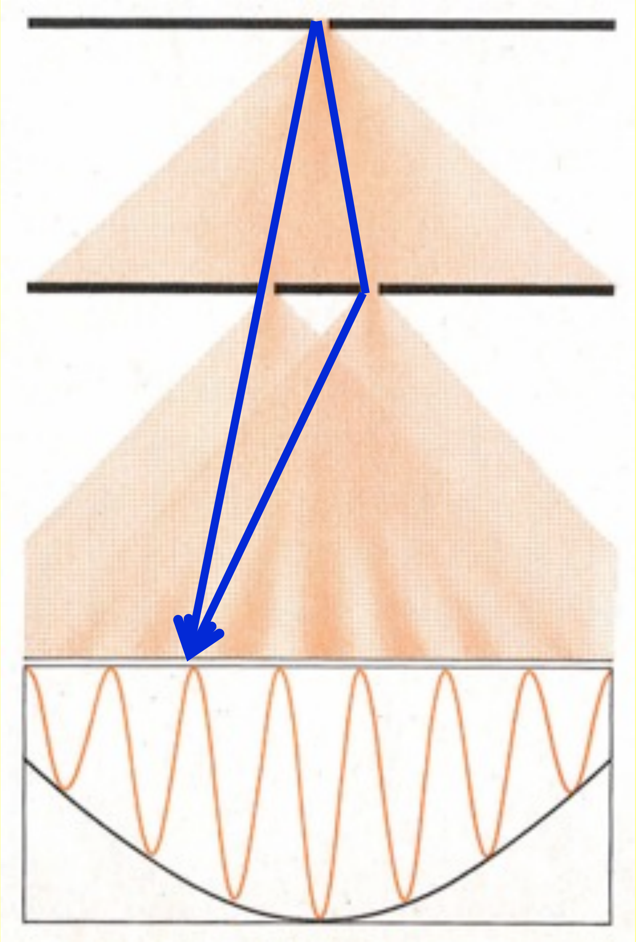

a
b
c
d
e



sand



photons, electrons

What interferes when electrons pass through the system of slits in the Young’s type experiment?

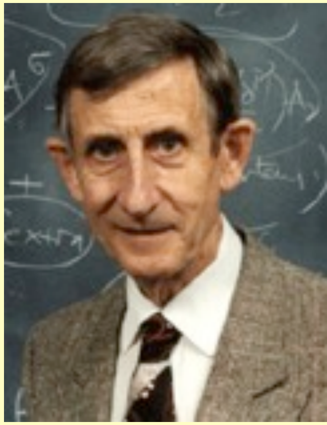
$$\Psi = \Psi_1 + \Psi_2$$

Ψ_1, Ψ_2 - wave functions for paths 1, 2 through slits 1, 2

„...I asked Bohr... Shall we ever understand atoms ?

Bohr hesitated for a while
and answered: Yes, but then we
shall also learn the meaning of the
word ”understand”

”Quantum electrodynamics gives us a complete description of the behaviour of the electron; therefore, in a certain sense, it allows us to understand the electron”



Freeman Dyson