Neutron discovery and atom completion

New experimental ideas in Early 20th Century Physics (1895-1932)

Particle physics history seminars

Jérémy Paltrinieri

The atom before 1895

The idea of the atom was vague, but many elements had been discovered and studied.

Classification by atomic weight by chemists: Newlands (1866), Mendeleev (1869)

Electrons, protons and neutrons yet to be discovered

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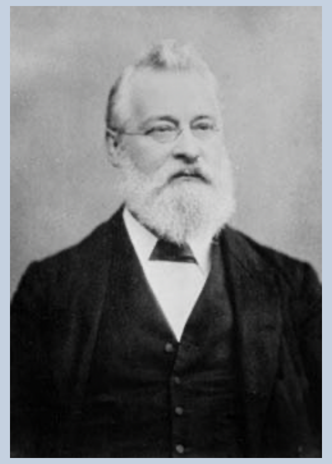

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C	H	1	F	8	Cl	15	Co & Ni	22	Br	29	Pd	36	I	42	Pt & Ir	50
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E	G	3	Mg	10	Ca	17	Zn	24	Sr	31	Cd	38	Ba & V	45	Hg	52
F	Bo	4	Al	11	Cr	19	Y	25	Ce & La	33	U	40	Ta	46	Tl	53
G	C	5	Si	12	Ti	18	In	26	Zr	32	Sn	39	W	47	Pb	54
A	N	6	P	13	Mn	20	As	27	Di & Mo	34	Sb	41	Nb	48	Bi	55
B	O	7	S	14	Fe	21	Se	28	Ro & Ru	35	Te	43	Au	49	Th	56

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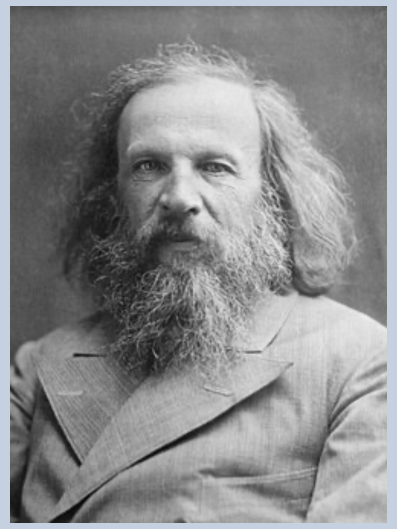

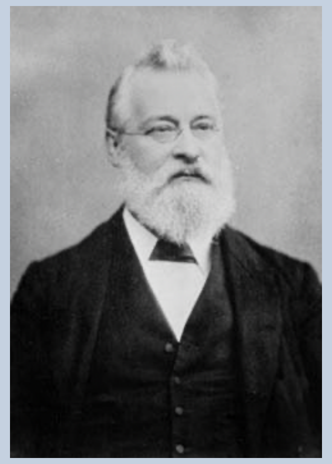

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Newlands' law of octaves

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

Mendeleev's periodic table

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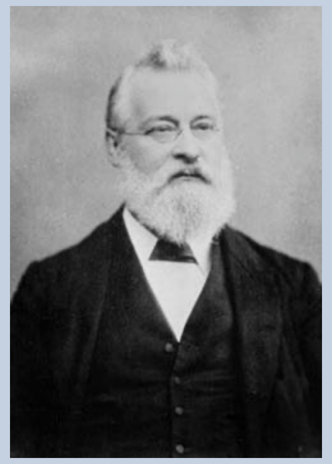

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Has inconsistencies

Not flexible

Doesn't work after Calcium

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C	H 1	F 8	Cl 15	Co & Ni 22	Br [illegible]	[illegible] 36	I 42	Pt & Ir 50
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E	G [illegible]	[illegible] 10	Ca [illegible]	[illegible] 24	Sr [illegible]	Cd 38	Ba & V 45	Hg 52
F	B [illegible] 4	Al 11	Cr [illegible]	Y 25	Ce [illegible] 33	U 40	Ta 46	Tl 53
G	C 5	Si 12	Ti [illegible]	In 26	[illegible] 32	Sn 39	W 47	Pb 54
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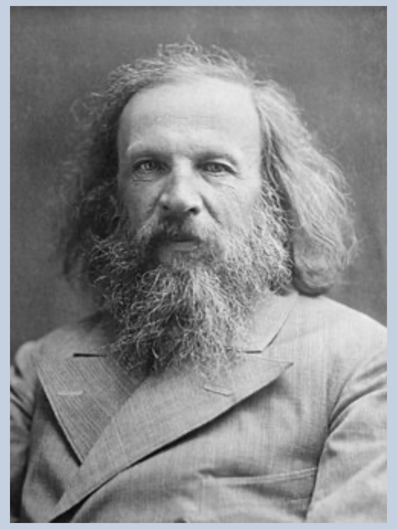

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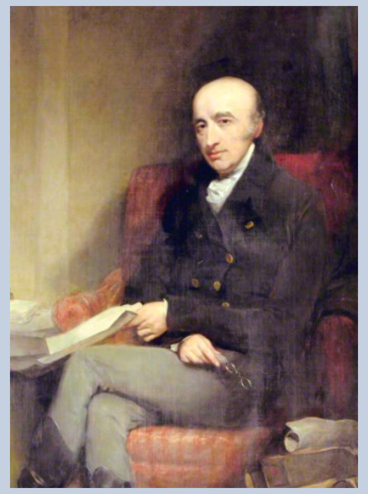
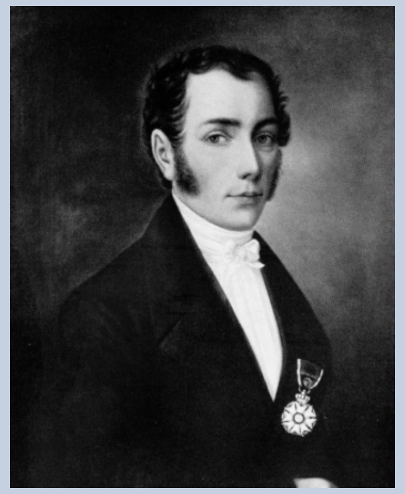
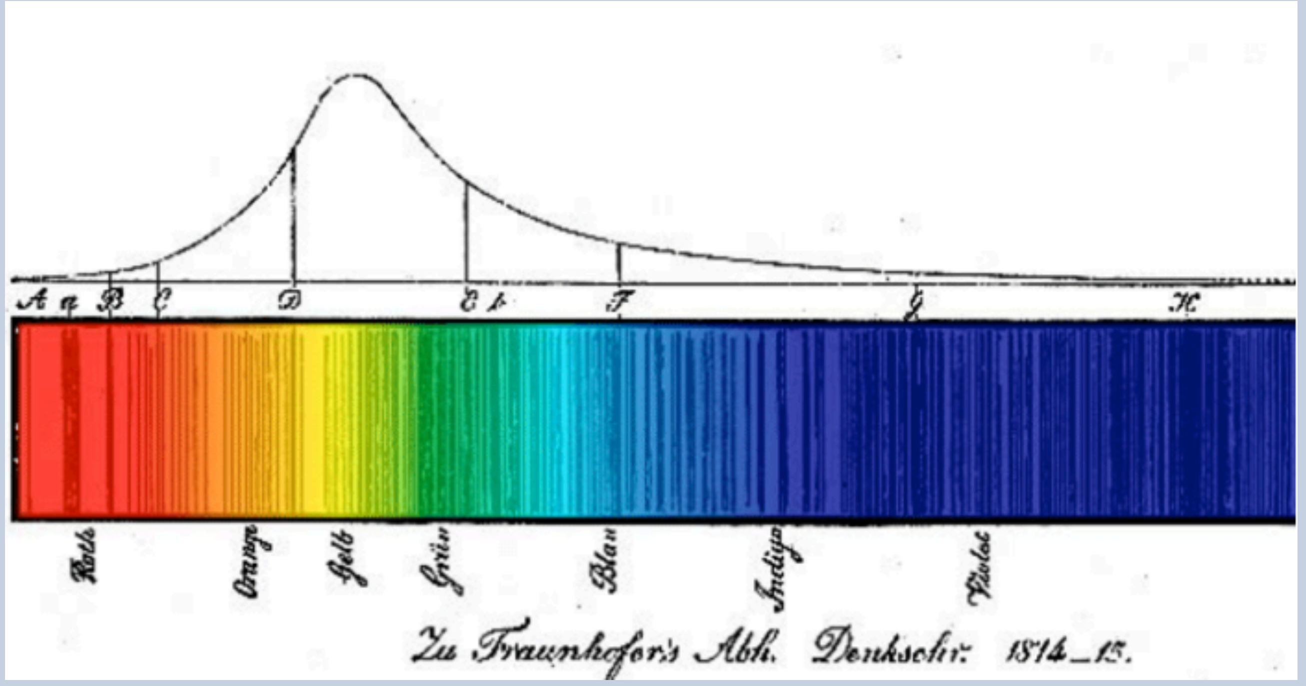
Spectral lines were studied: Young, Wollaston, Fraunhofer from sunlight







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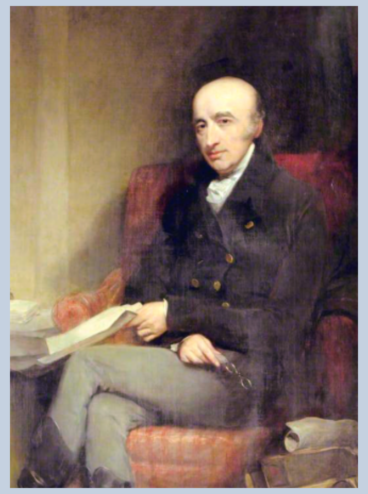
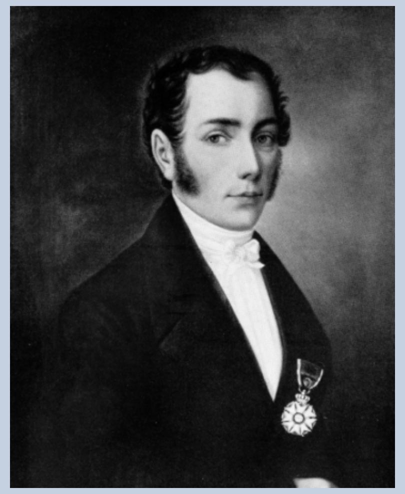
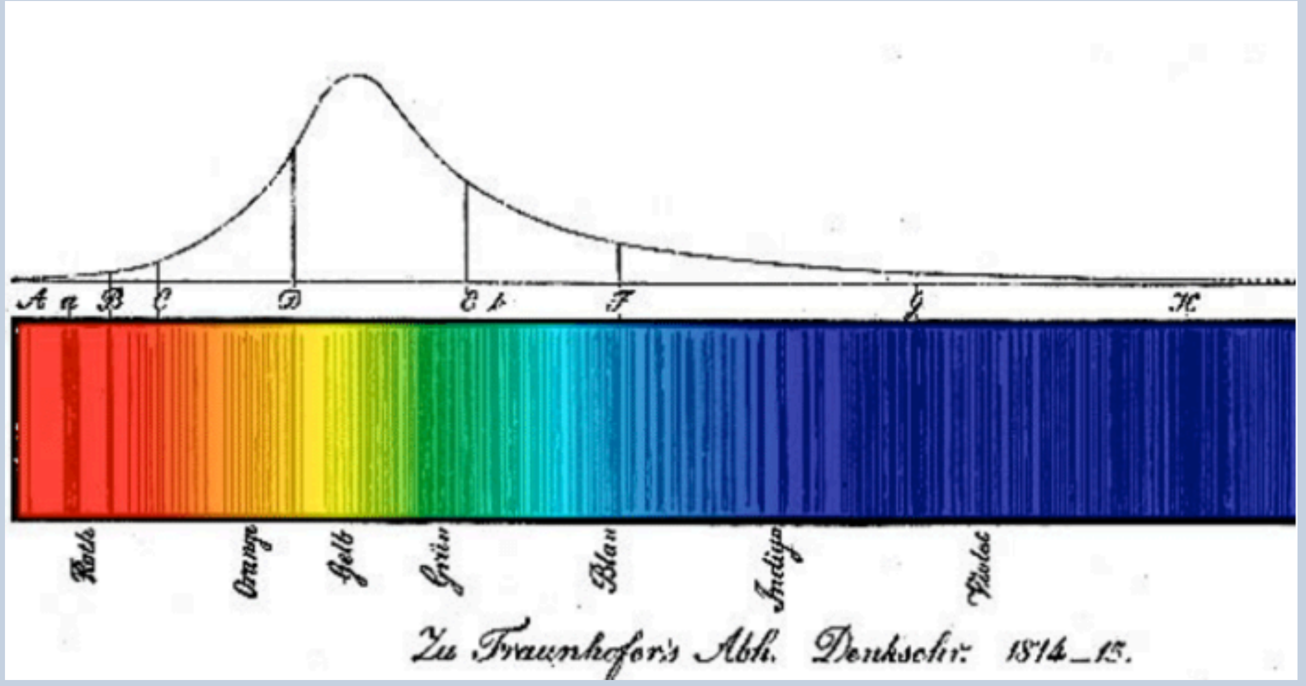
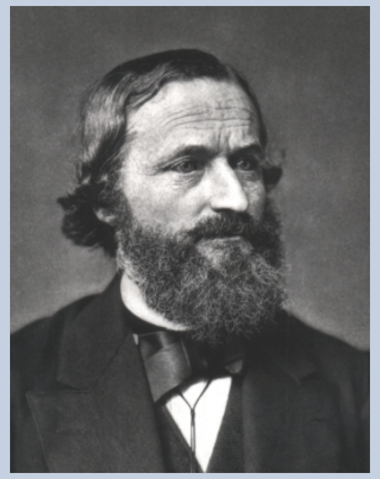
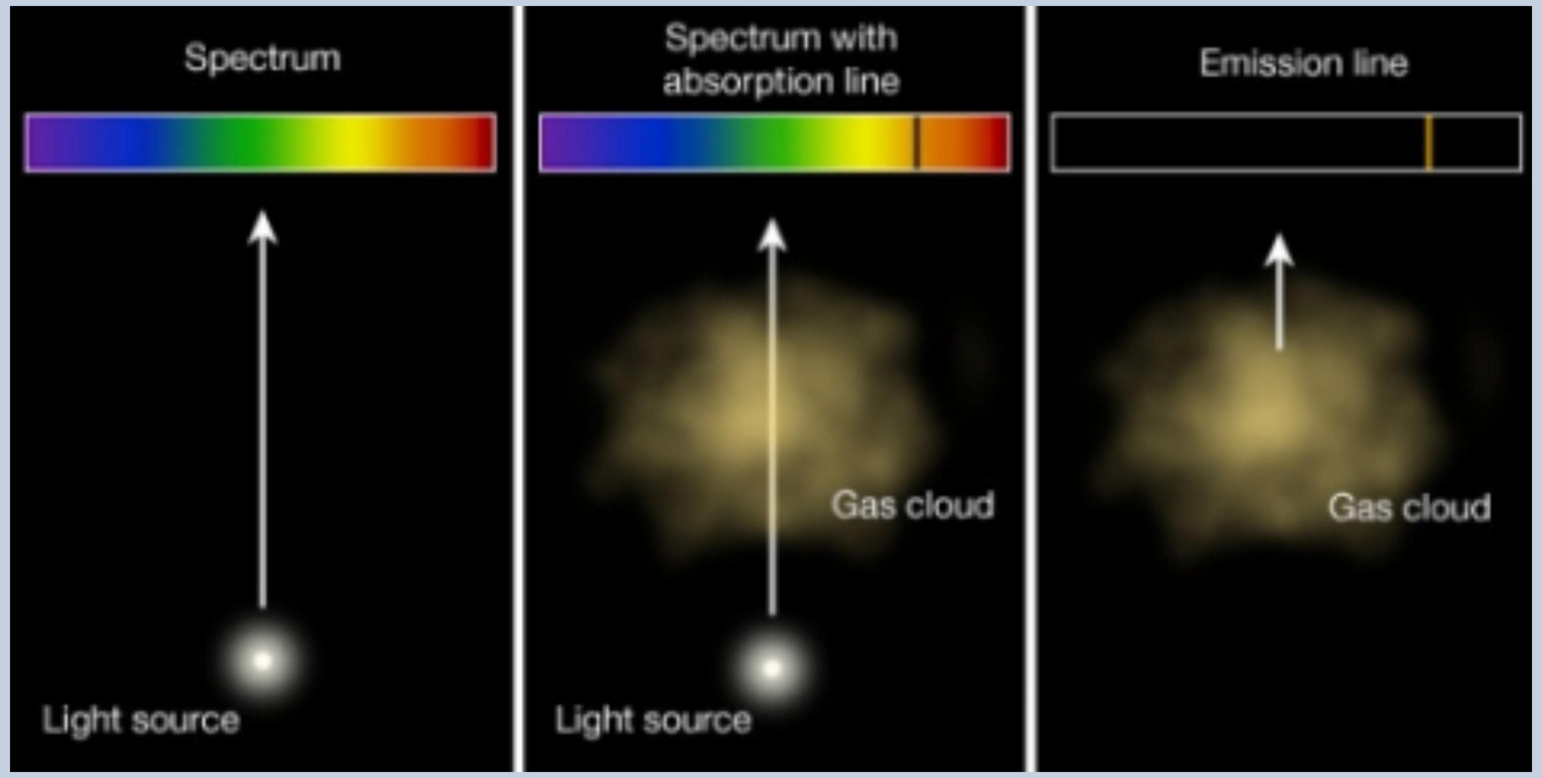






Kirchhoff: continuous, absorption and emission spectra:





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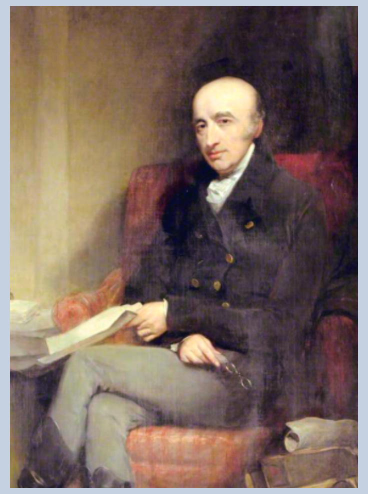

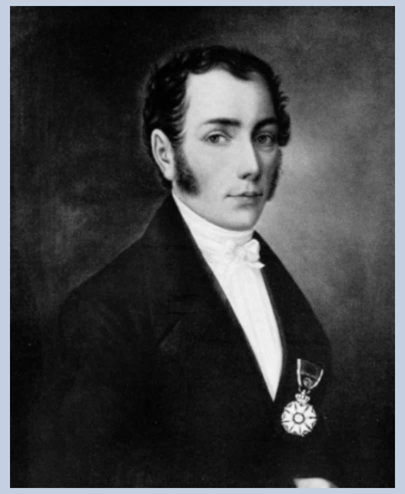

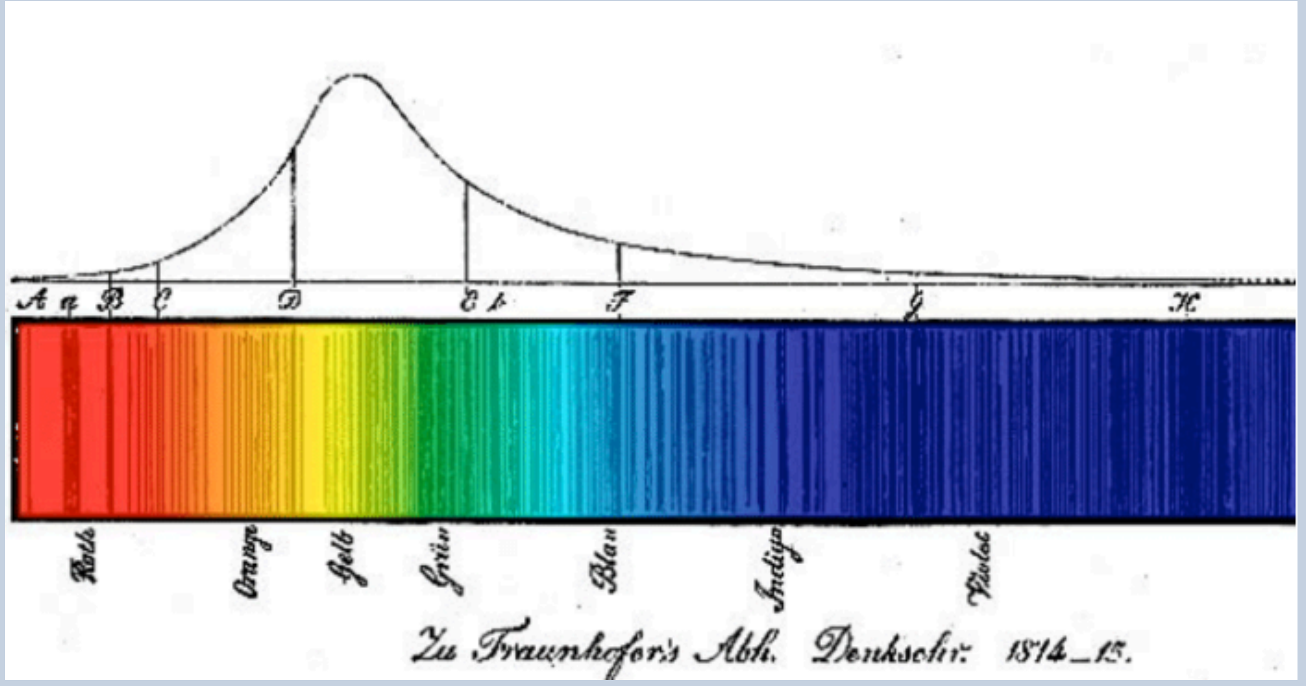

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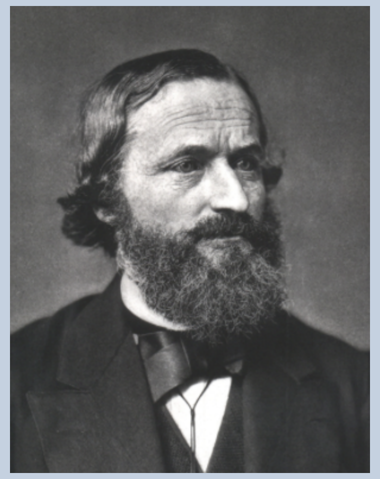
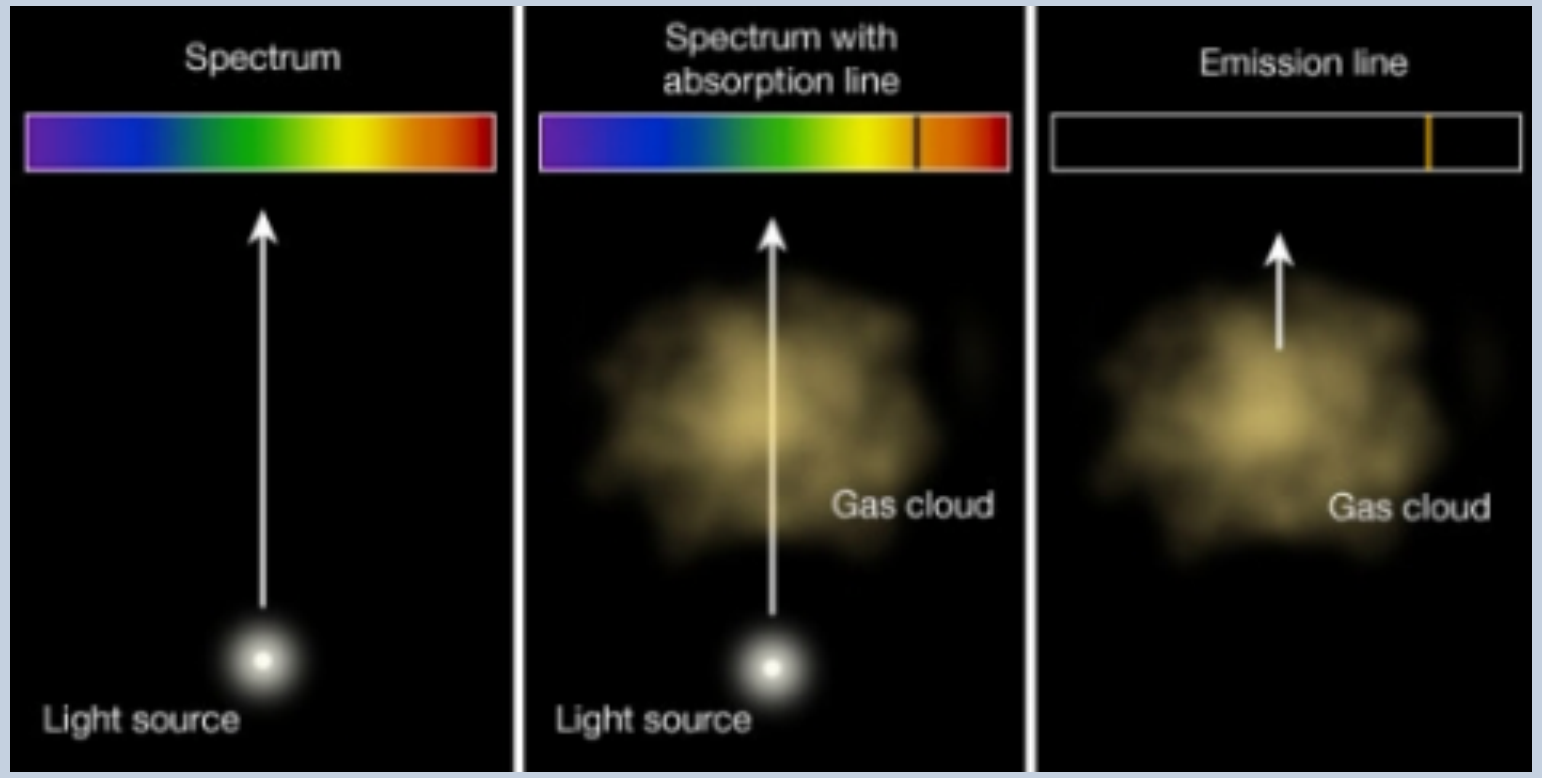
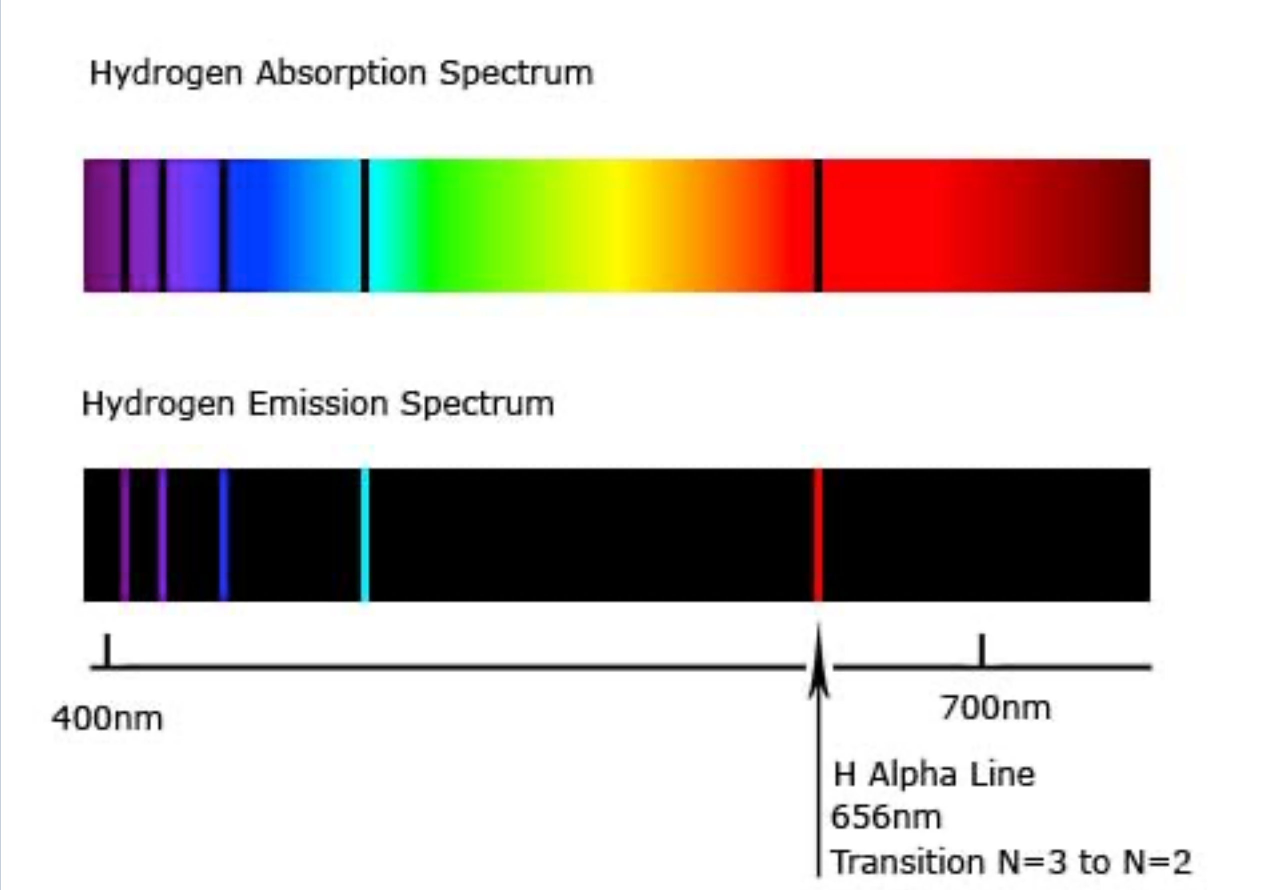




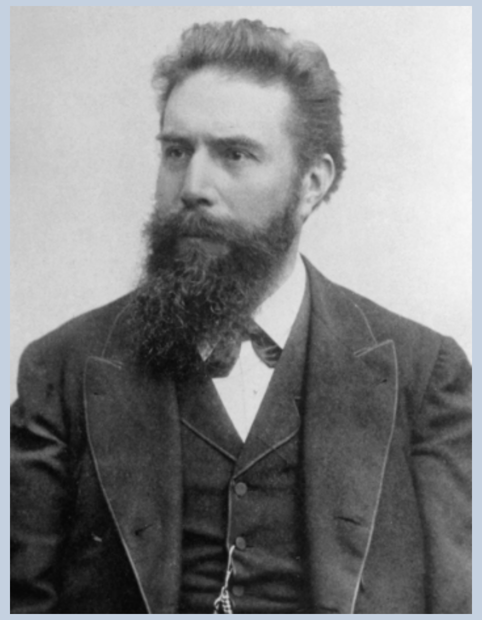
Balmer: formula for the wavelength of hydrogen (empirical):

$$\lambda = h\frac{n^2}{n^2 - 2^2}$$



X-Rays and Radioactivity (1895)

Discovery of X-rays by Röntgen in 1895 ⟶ First Nobel Prize in Physics in 1901



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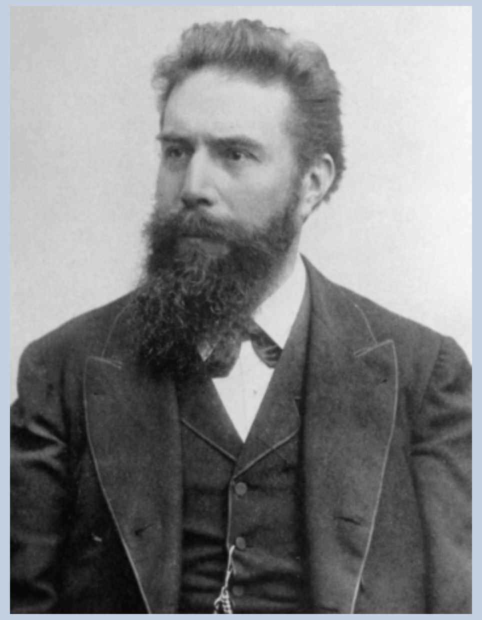

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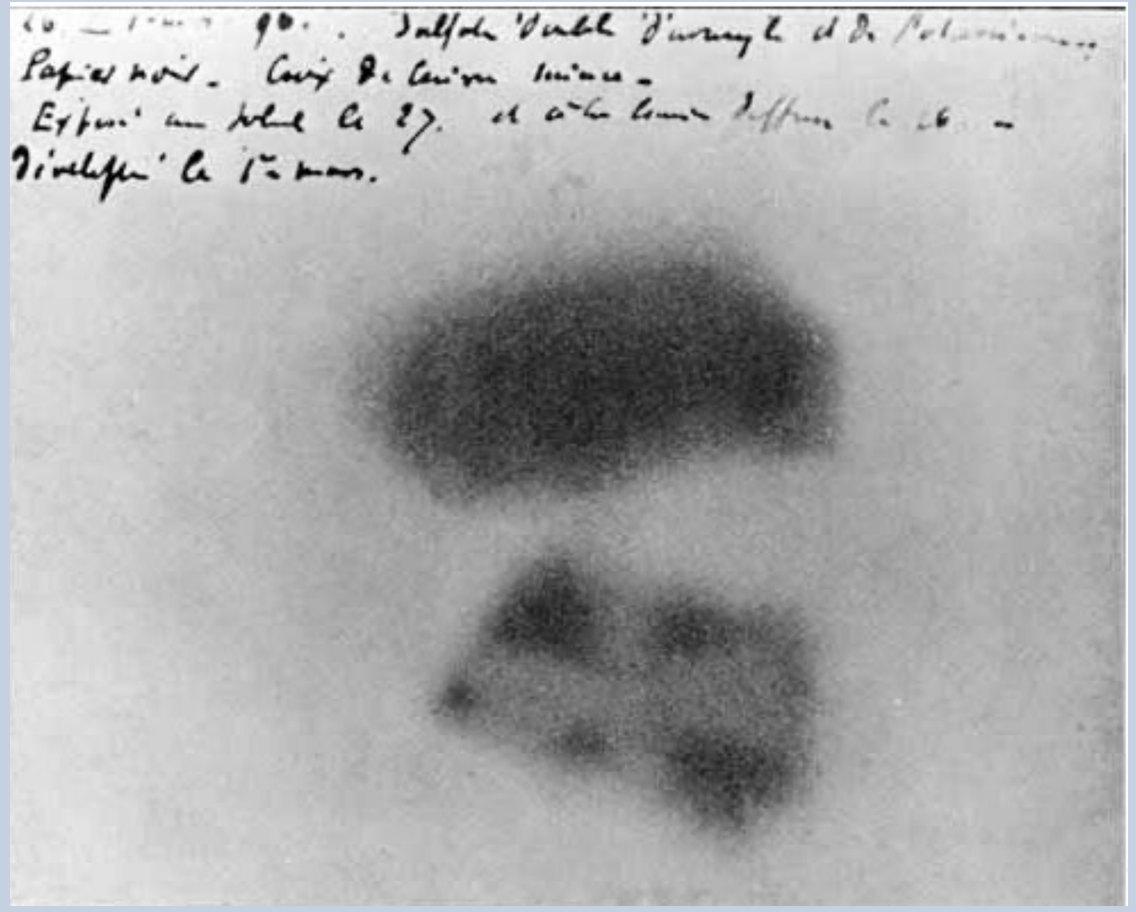

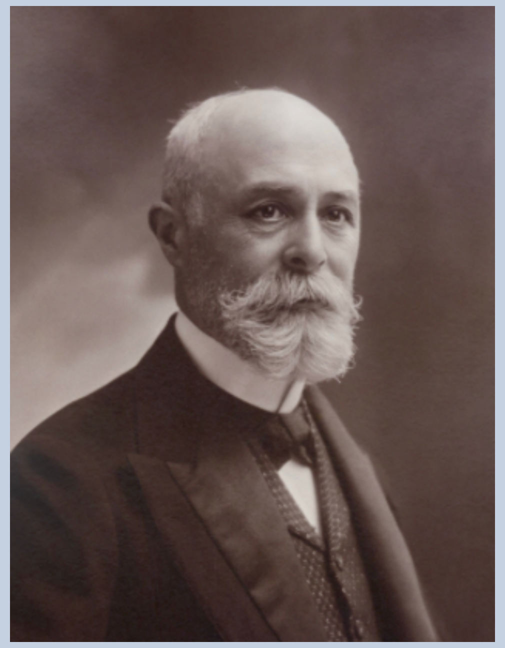

1903

Uranium darkens photographic plates

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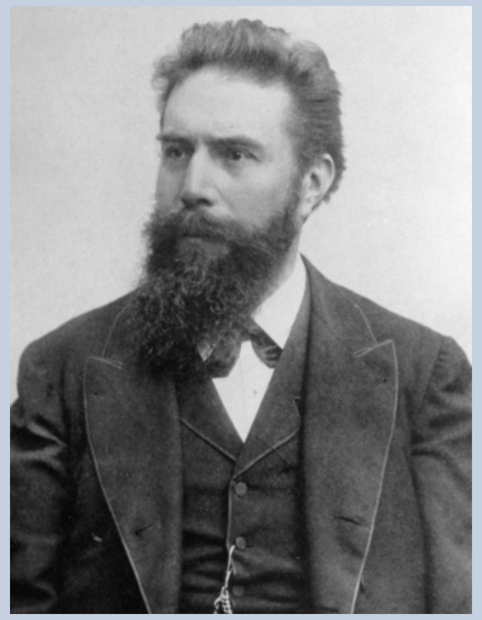

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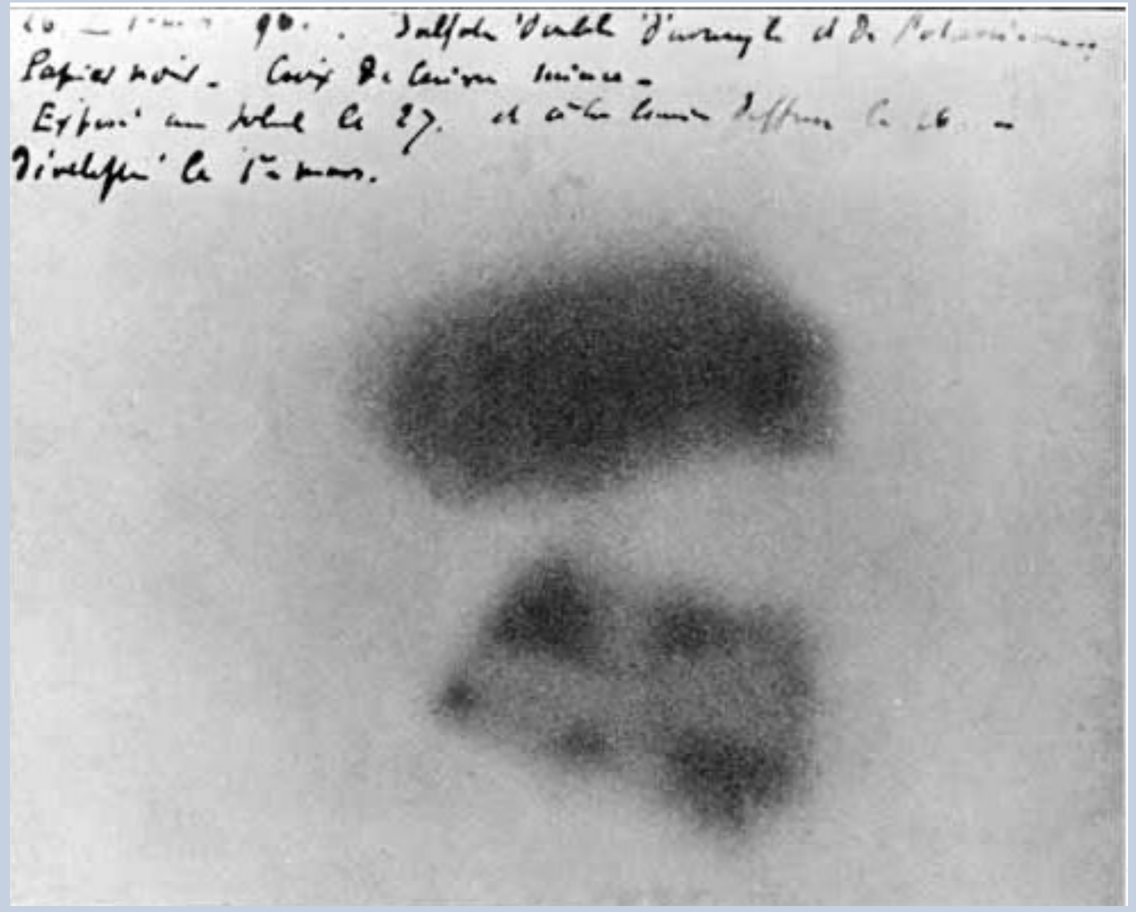
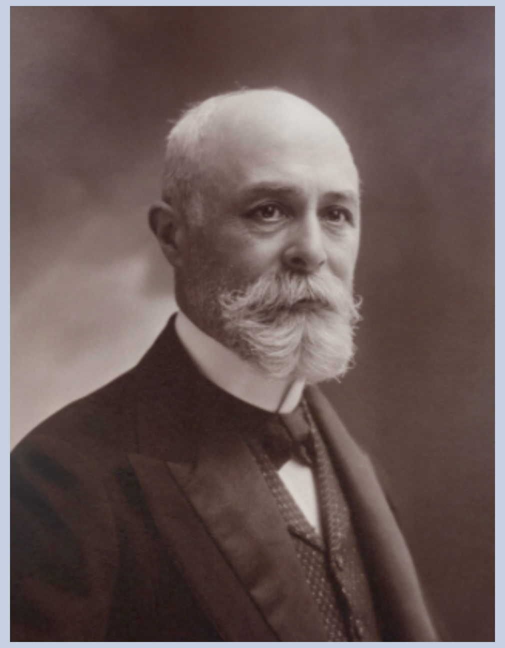




1903

Marie Curie discovered Polonium and Radium

1903-1911

Uranium darkens photographic plates

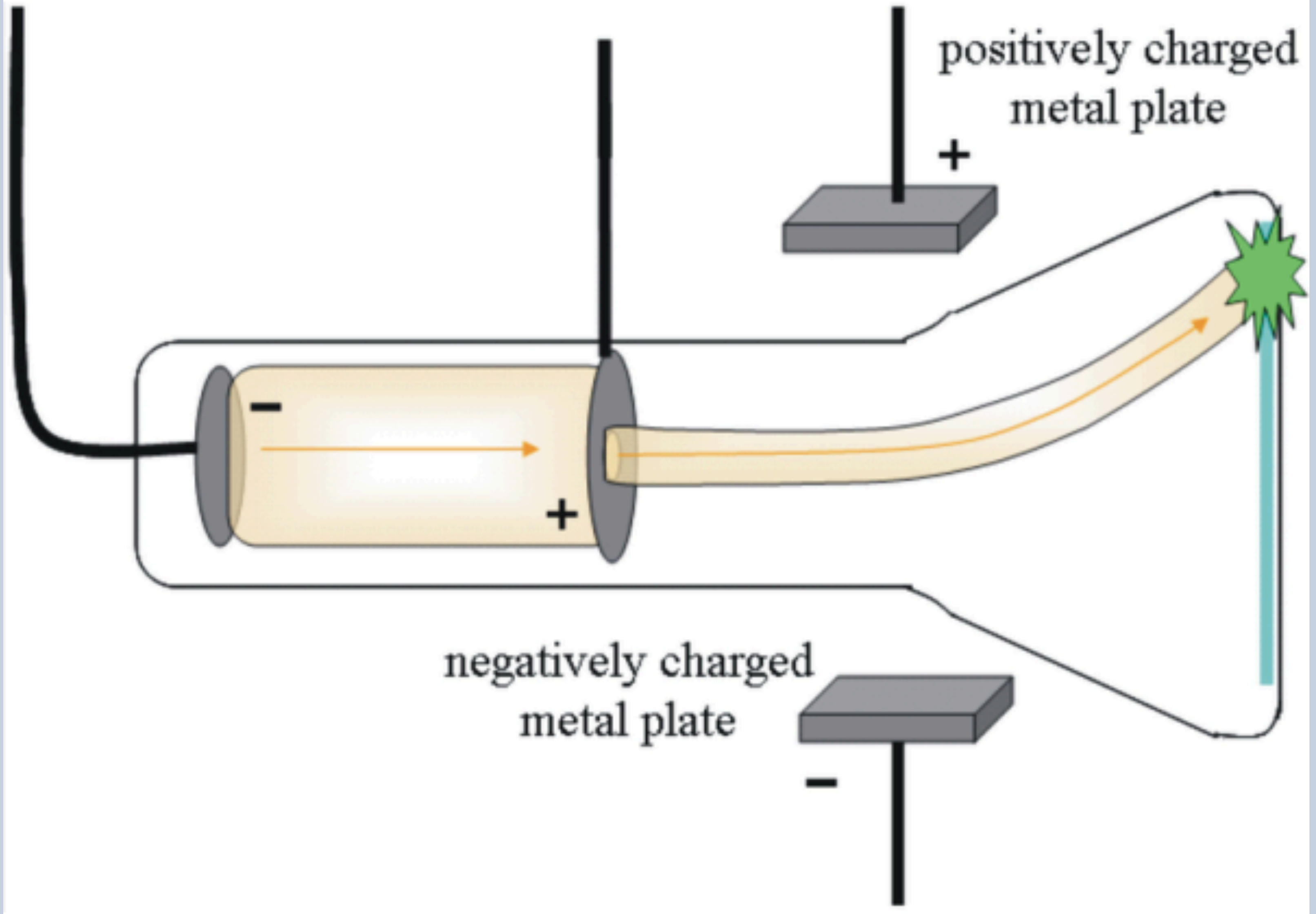
Cathode rays and the discovery of the electron by J. J. Thomson (1897)

Up to then, people used cathode rays but did not know what they were

Assumed to be some sort of uncharged electromagnetic waves

Thomson proved that they were actually particules, negatively charged

1906

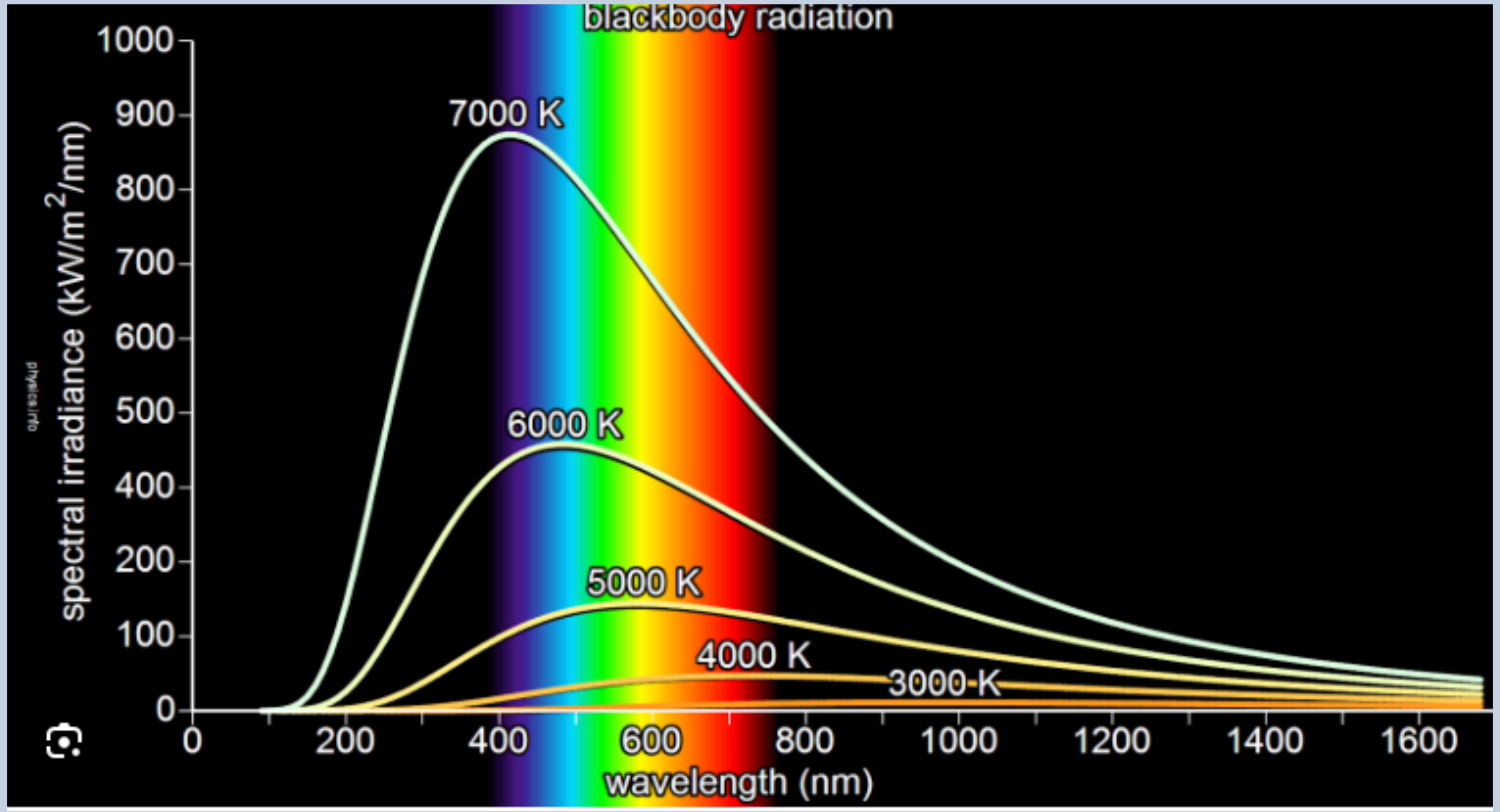


Cathode rays: two charged plates produce a light at the end of the glass chamber: why?

To study it, put metal plates or magnets around

Charge to mass ratio was non-compatible with more massive ions that were known

The particle is universal: doesn’t depend on the metal used for the diode

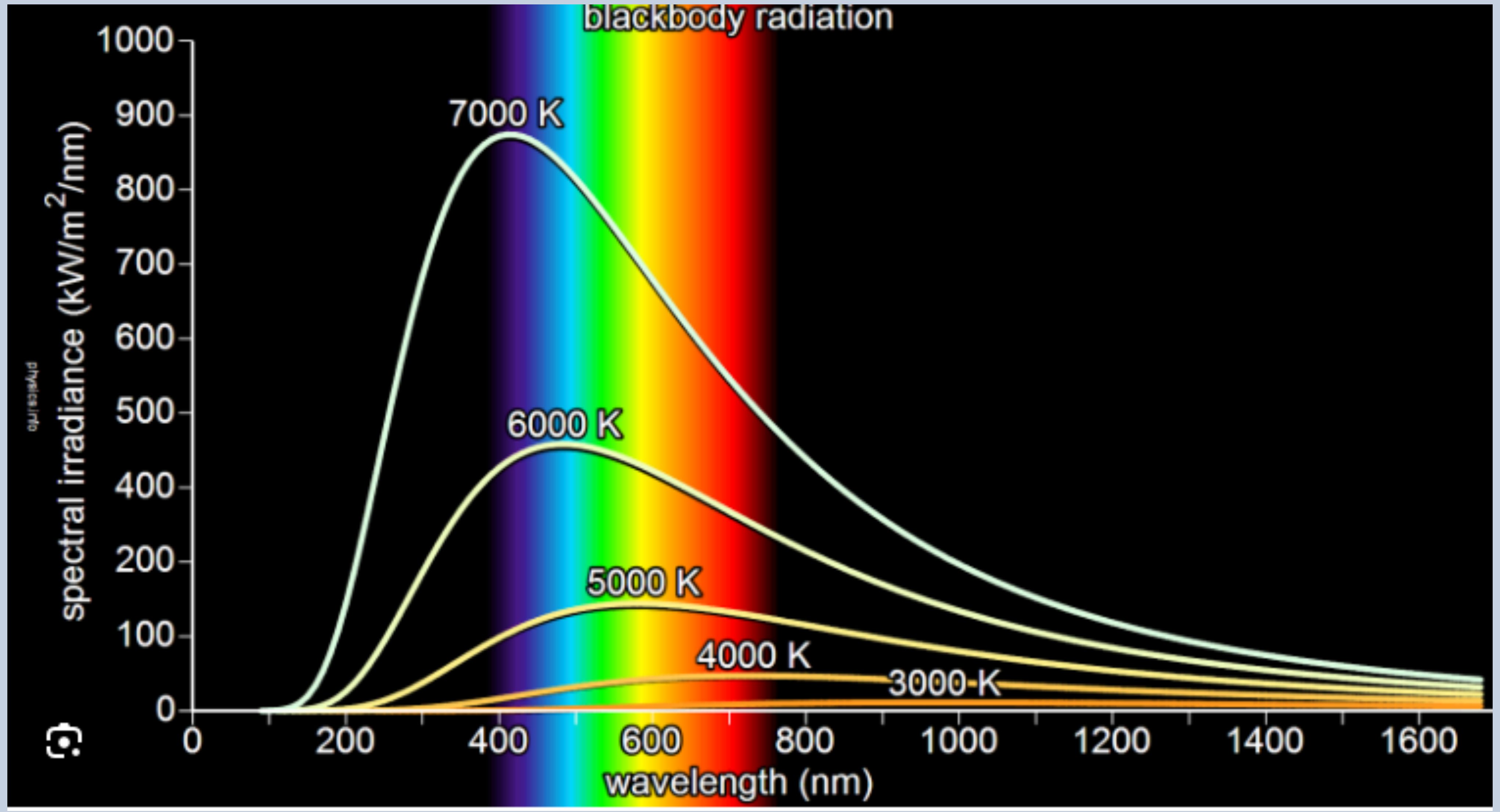


1918

Planck's proposed quantisation of energy of oscillators in blackbodies to derive the formula for spectral radiance as function of wavelength and temperature

$$I(\nu) = \frac{8\pi kT}{c^3}\nu^2$$

Classical description



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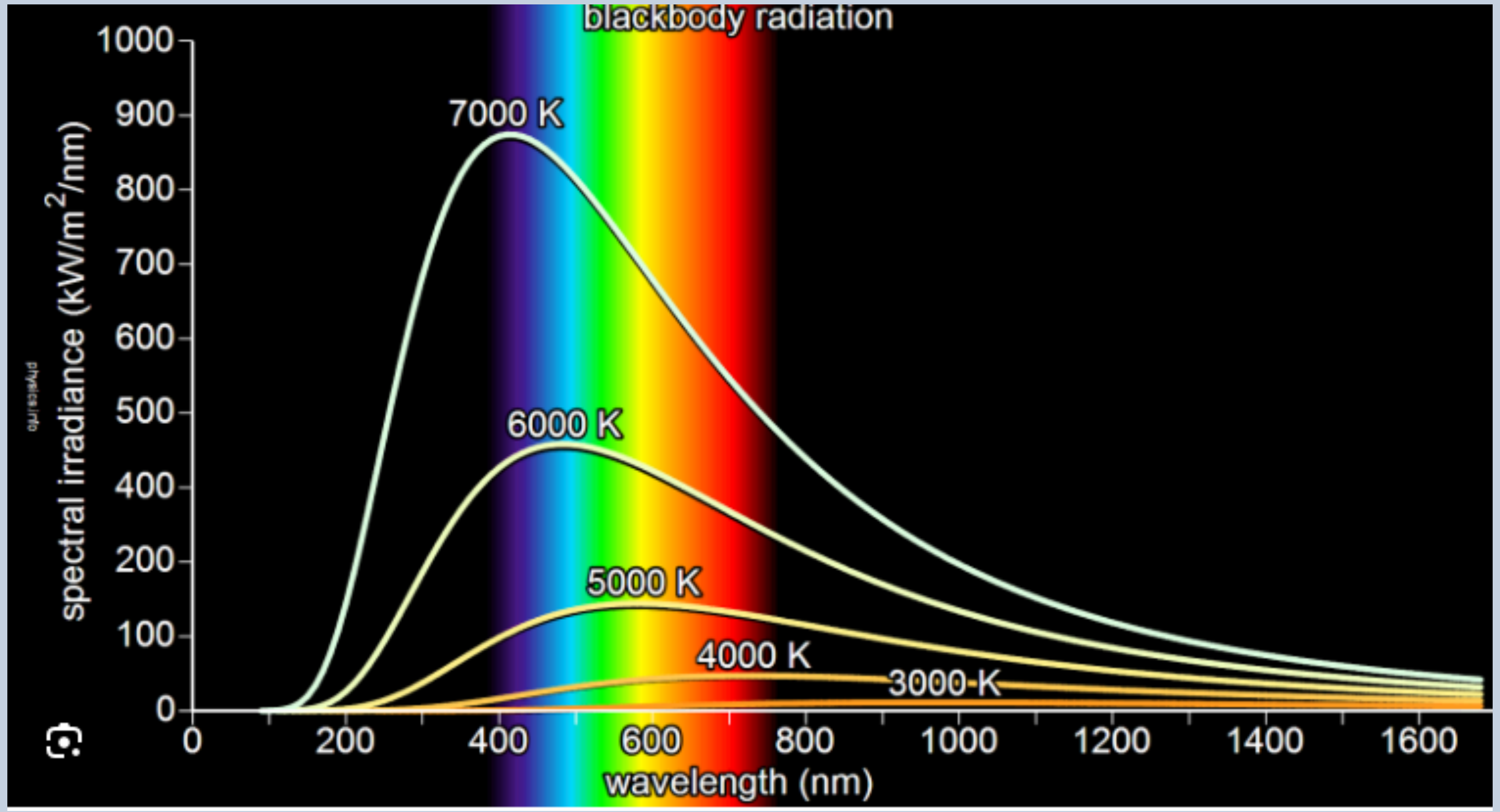
$$I(\nu, T) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT} - 1}$$

Classical description

"Quantum" description



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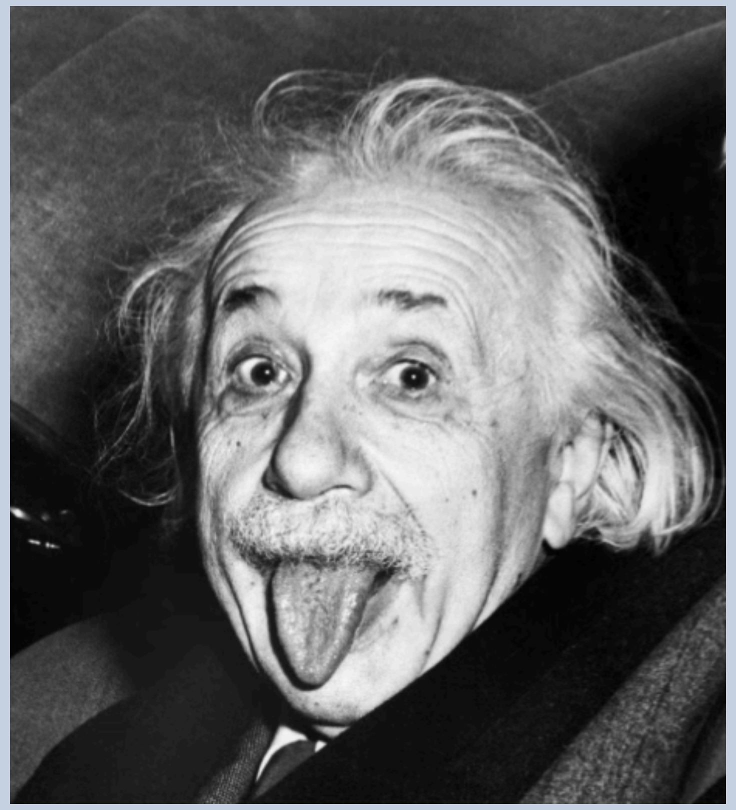

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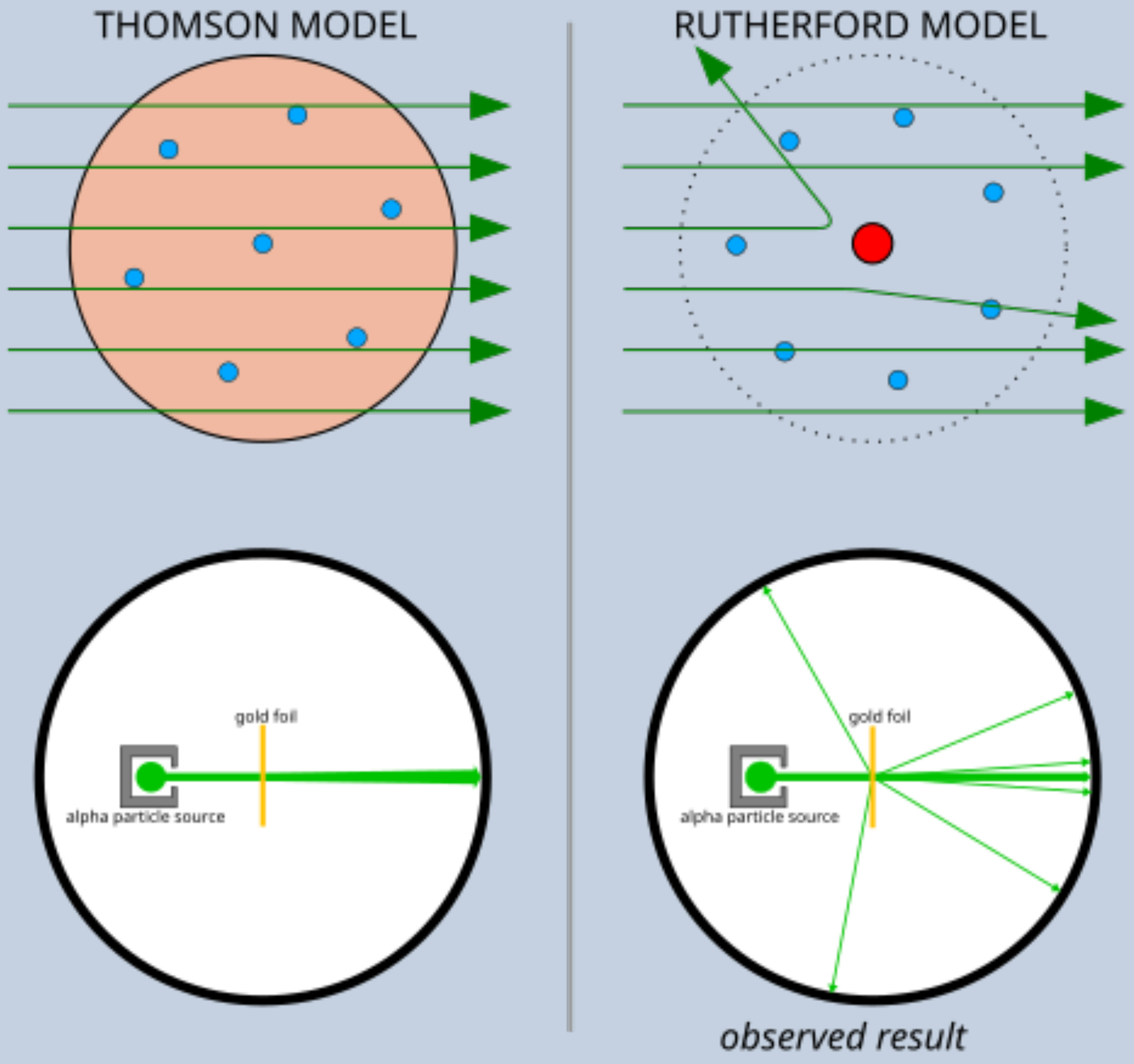
Einstein built on this and explained the photoelectric effect

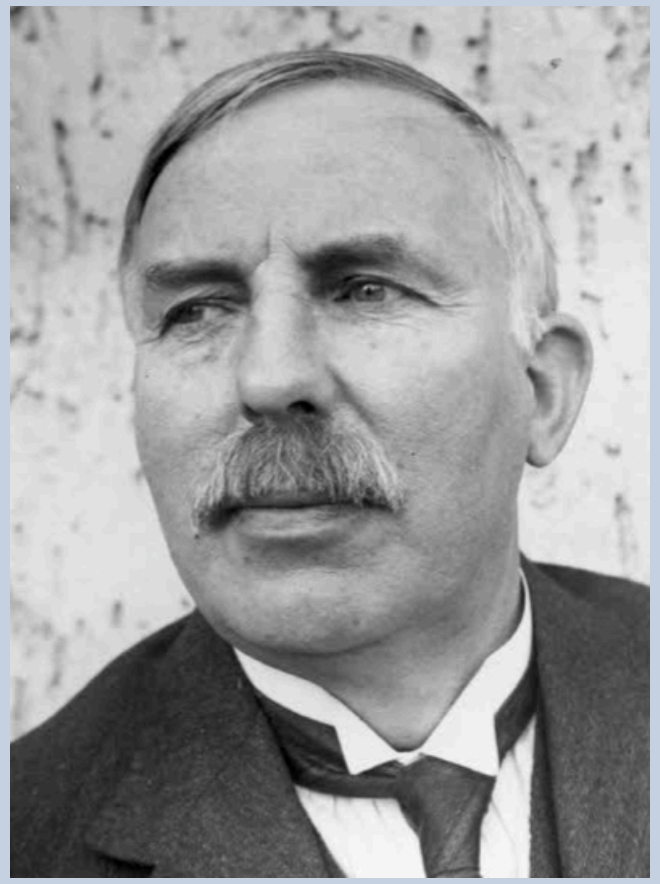
Rutherford's Gold Foil Experiment (1907)

To probe the structure of atoms, Rutherford shot alpha particles to a gold foil target



1908

(Chemistry)



Expected low angle scattering from electrons which bathe in a cloud of positively charged substance
Observed large angle scattering

Plum pudding of positively charged particles is not right: atom has a small charged nucleus

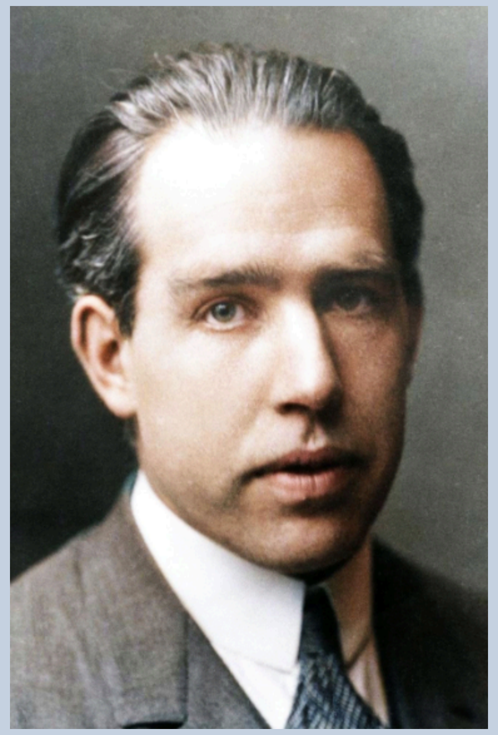
Atomic Number and Isotopes: Bohr, von Laue, Moseley

The atom's size was not fixed by the experiments listed before

A bit of dimensional analysis shows that you can construct a length from m, e and Planck's constant:

$$a_0 = \bar{h}^2/(m_e e^2) = 0.529\text{Å}$$

Heavier atoms' structures was still very obscure



1922

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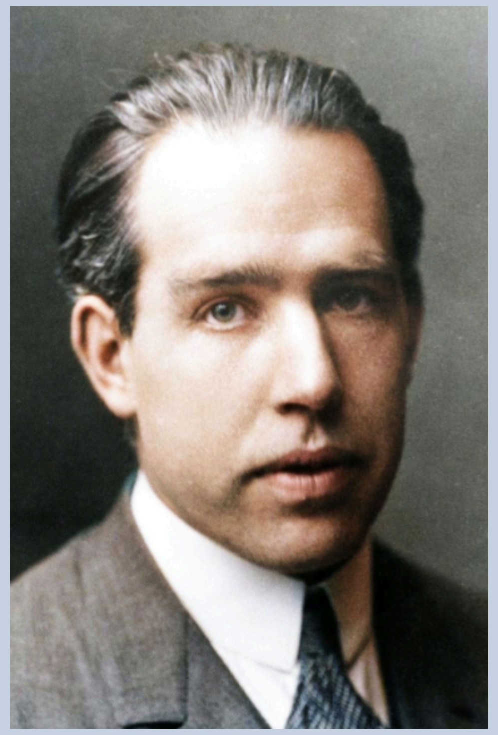
- X-rays are electromagnetic waves
- They undergo diffraction in crystals: the patterns can be used to study the metals at the origin of the X-rays



1922

1914

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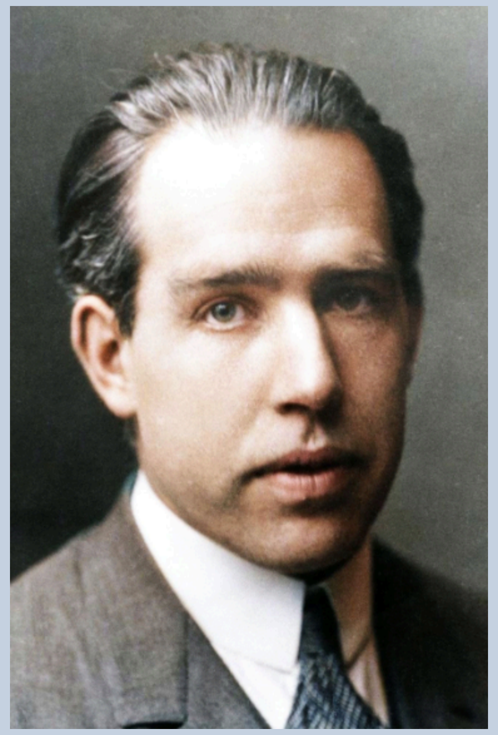

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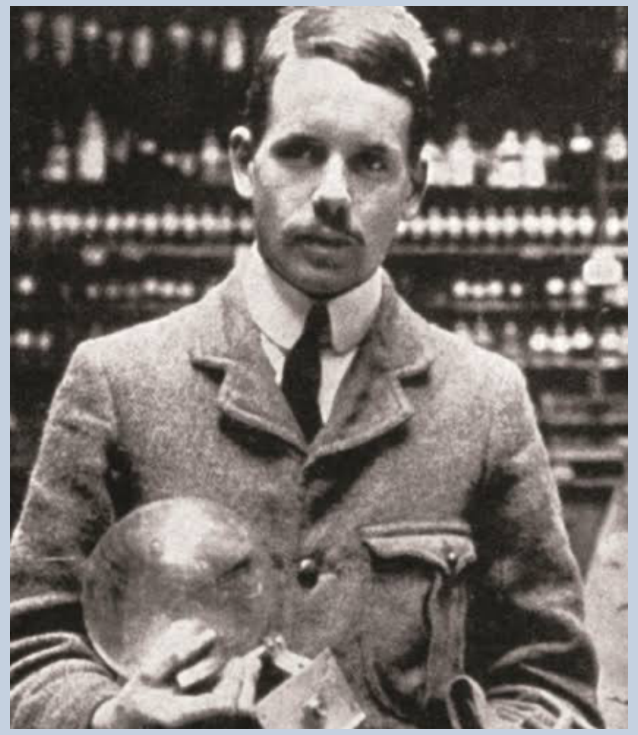
Moseley built on this and found the empirical formula:

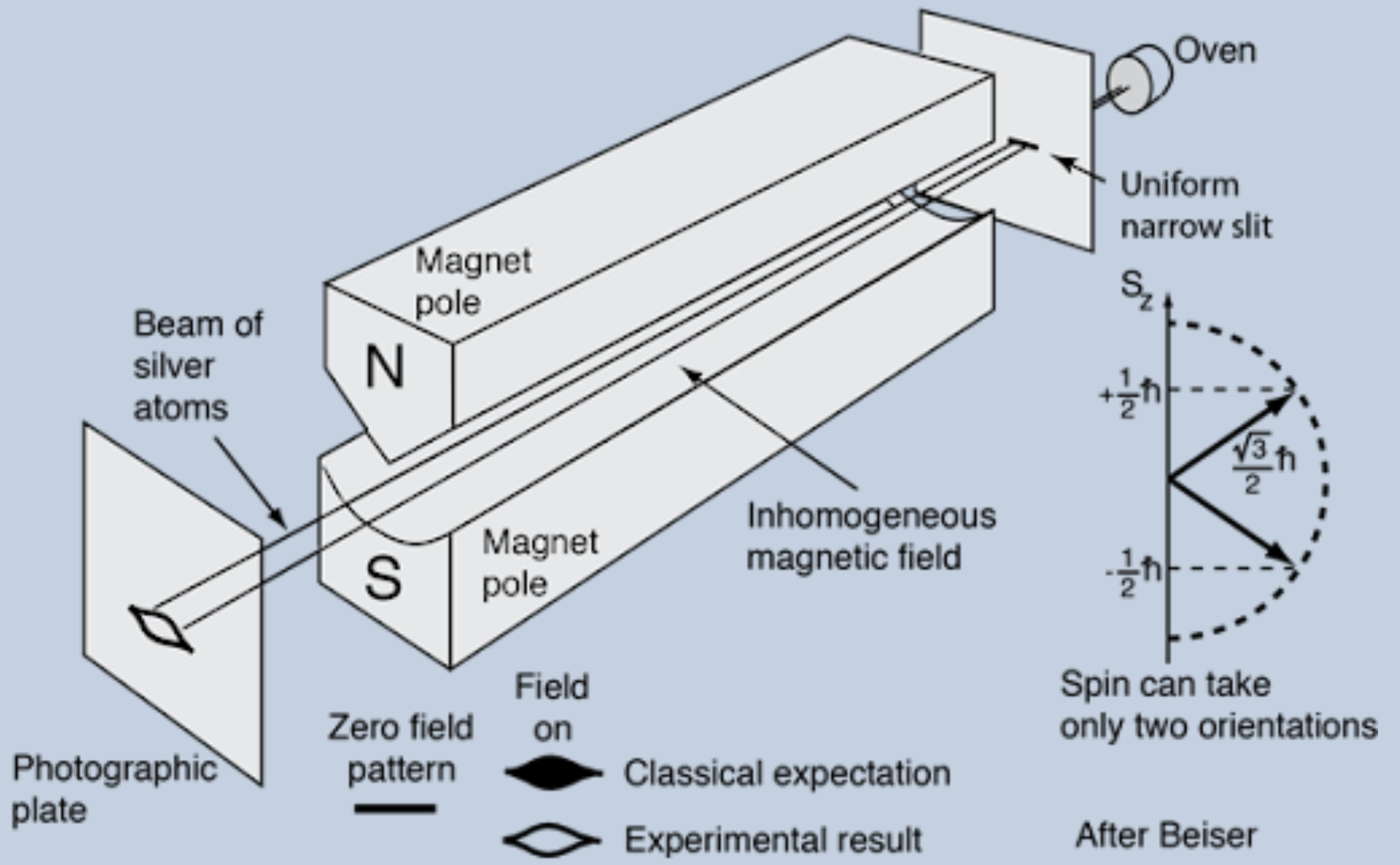
$$\nu = \nu_0(n - a)^2$$



n is the positive charge of the nucleus! Can order elements
Discovery of isotopes

Emergence of the understanding of spin: fermions and bosons

Electrons and protons: spin 1/2, alpha particle: spin 0, deuterium: spin 1



Stern-Gerlach experiment: the intrinsic angular moment of the electron is quantised!

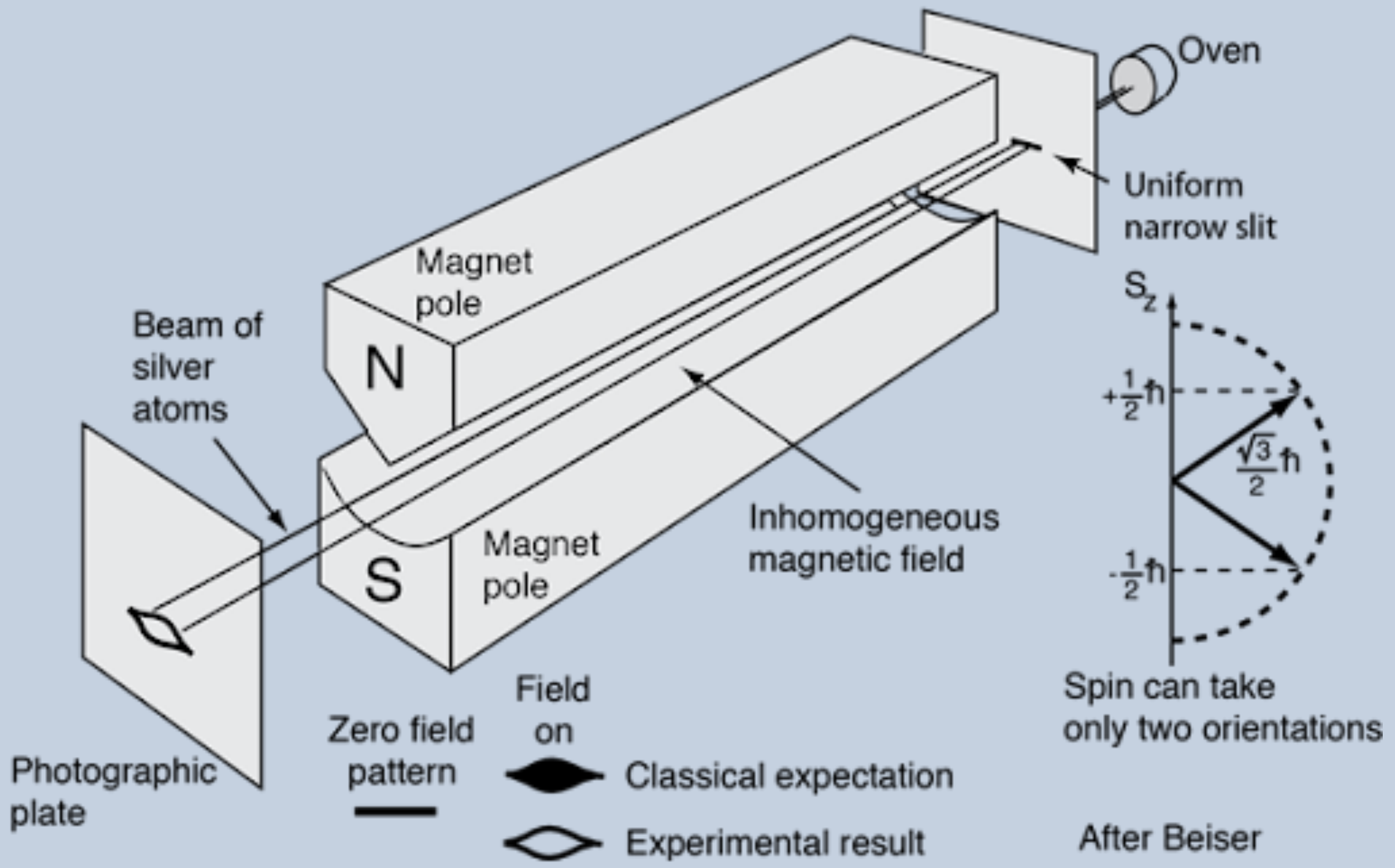
Nuclear Puzzle: Rasetti determination of the spin of Nitrogen

Emergence of the understanding of spin: fermions and bosons

Electrons and protons: spin 1/2, alpha particle: spin 0, deuterium: spin 1

Problem with the nitrogen N_7^{14} nucleus:

- If it contains 14 protons and 7 electrons, it should be a fermion
- It was shown to have spin 1 by Ornstein and van Wyk
- It was shown to be a boson by Rasetti



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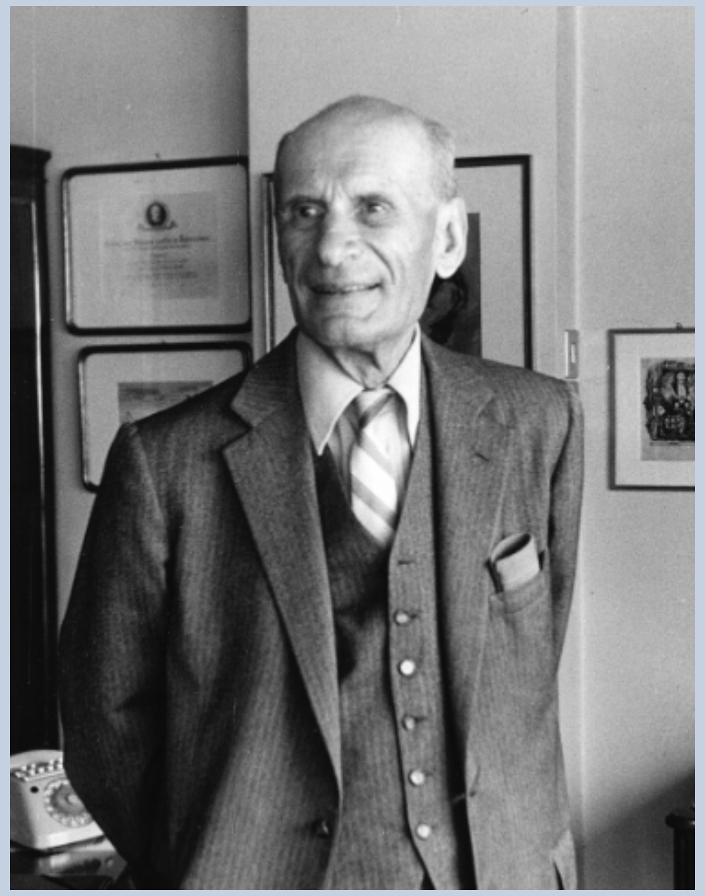

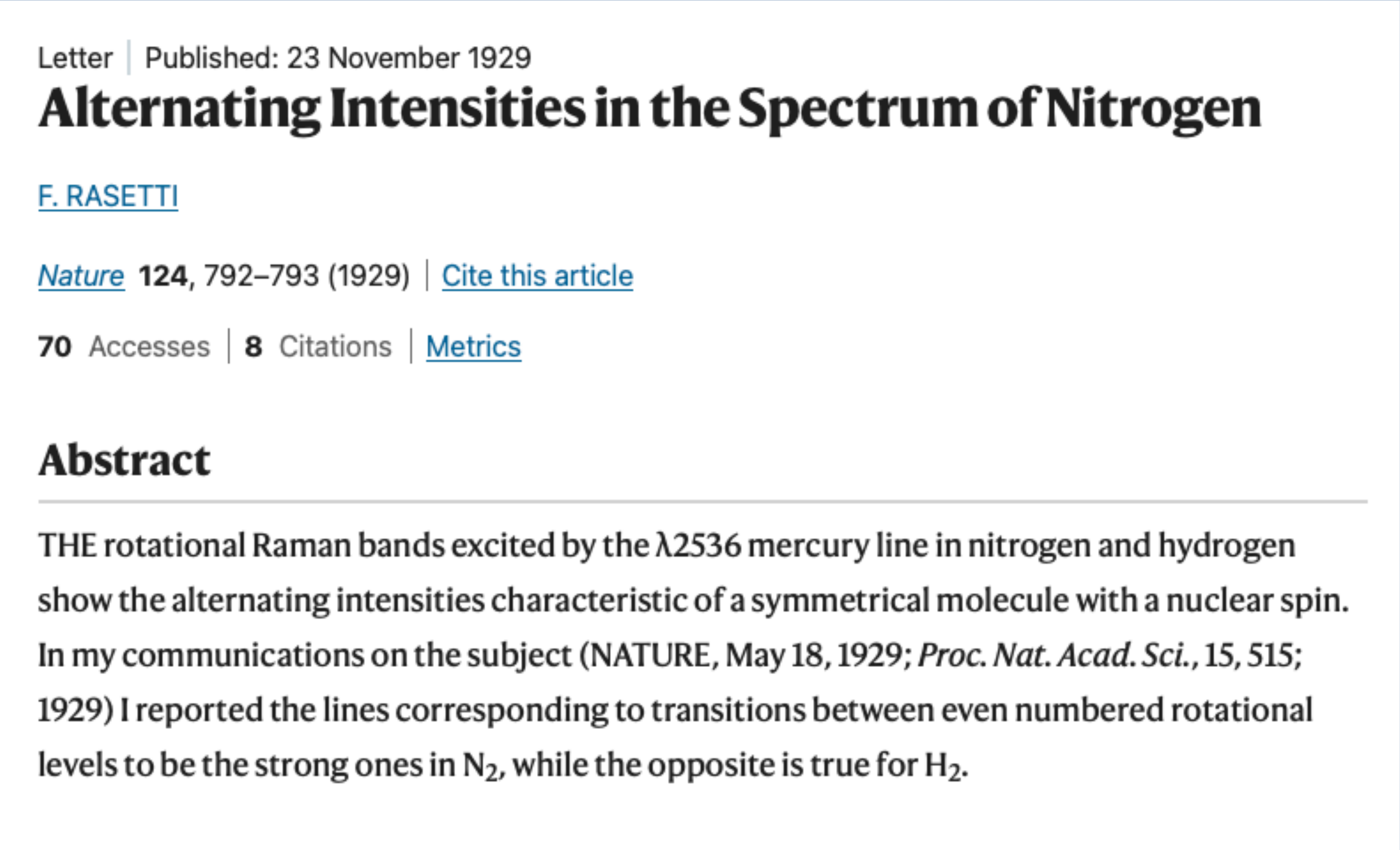

Letter | Published: 23 November 1929

Alternating Intensities in the Spectrum of Nitrogen

F. RASETTI

Nature **124**, 792–793 (1929) | Cite this article

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Abstract

THE rotational Raman bands excited by the λ2536 mercury line in nitrogen and hydrogen show the alternating intensities characteristic of a symmetrical molecule with a nuclear spin. In my communications on the subject (NATURE, May 18, 1929; *Proc. Nat. Acad. Sci.*, 15, 515; 1929) I reported the lines corresponding to transitions between even numbered rotational levels to be the strong ones in N_2, while the opposite is true for H_2.

Nuclear Puzzle: Rasetti determination of the spin of Nitrogen

Raman scattering: incident light: mercury line at $\lambda = 2536\text{Å}$

Scattered light shows Raman bands corresponding to change in rotational energy: $\Delta J = \pm 2$

Intensity of the bands depends on:

1) how many molecules are on the J level initially
2) whether the new J is allowed by nuclear spin statistics

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Hydrogen (H2)

Each nucleus = proton, spin 1/2

Total spin can be:

- 1 (triplet, symmetric)
- 0 (singlet, antisymmetric)

3 Sym. spin states combine with odd J

1 Antisym. spin state combines with even J

Odd J lines stronger (x3)

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Nitrogen (N2)

Each nucleus = 14N, spin 1

Total spin can be:

- 0 or 2 (symmetric)
- 1 (antisymmetric)

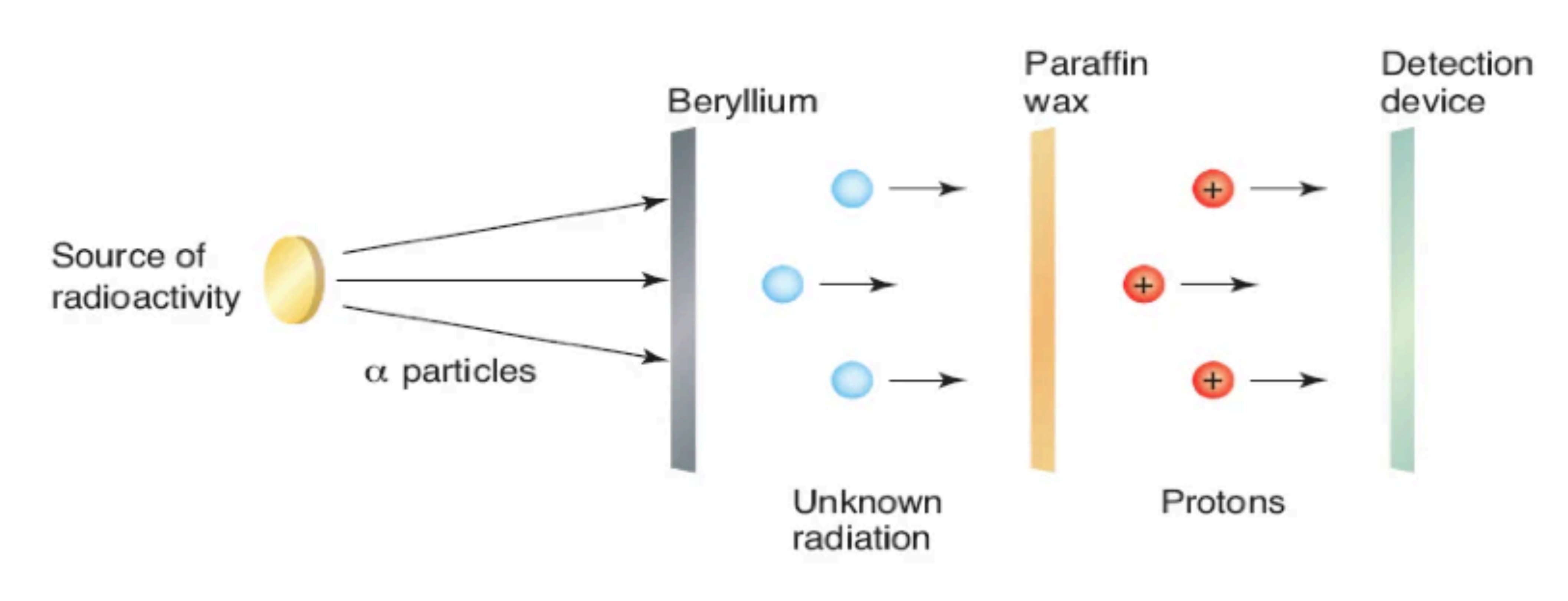
6 Sym. spin states combine with even J

3 Antisym spin states combines with odd J

Even J lines are stronger (x2)

Bothe, Becker, Juliot, Curie's experiment (1932)

Shooting alpha particles again, onto a beryllium target this time



Bothe and Becker experiment improved by Juliot and Curie

When energetic alpha particles hit light elements, an unknown, penetrating radiation was emitted

Juliot-Curie idea: put a paraffin wax (containing hydrogen) to study the radiation

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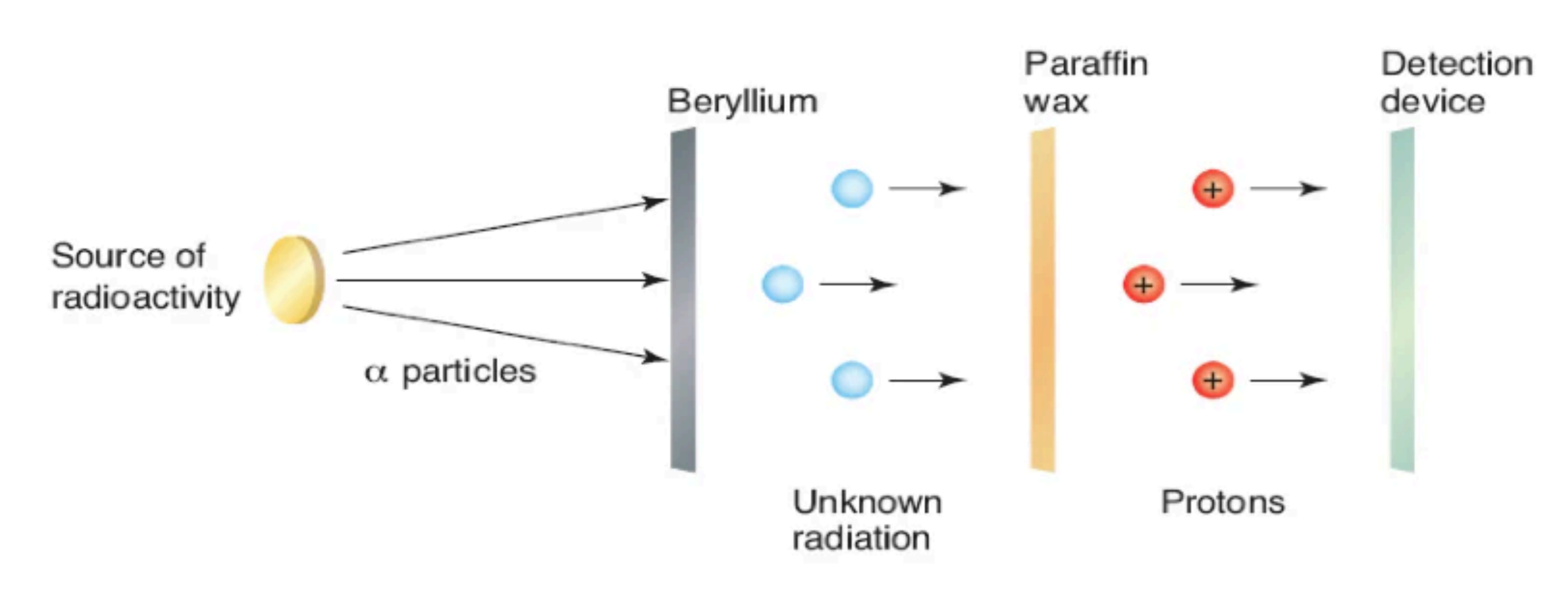

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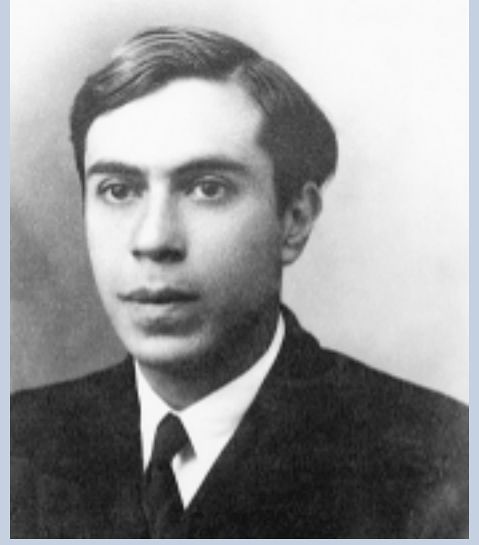

Majorana interpreted this as a neutron but didn't publish it despite Fermi's encouragement to do so

Observations:

- the radiation is uncharged (isn't influenced by an electric field)
- the radiation produced ejected protons at high energies (5 MeV)

If it was a gamma ray (uncharged), its energy would have to be 50 MeV

Incompatible with energy of the alpha particles from polonium decay

The neutron discovery: Chadwick's experiment (1932)

The Existence of a Neutron
Author(s): J. Chadwick
Source: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, Vol. 136, No. 830 (Jun. 1, 1932), pp. 692-708
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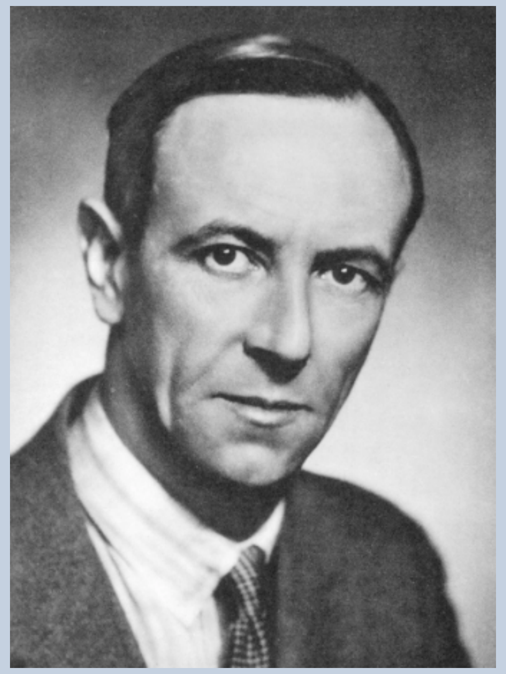

Assuming Compton scattering

For beryllium: $v_p = 3 \times 10^9\, m/s \rightarrow E_\gamma = 50\, MeV$

For boron: $E_\gamma = 35\, MeV$

There are two grave difficulties in such an explanation of this phenomenon. Firstly, it is now well established that the frequency of scattering of high energy quanta by electrons is given with fair accuracy by the Klein-Nishina formula, and this formula should also apply to the scattering of quanta by a proton. The observed frequency of the proton scattering is, however, many thousand times greater than that predicted by this formula. Secondly, it is difficult to account for the production of a quantum of 50×10^6 electron volts from the interaction of a beryllium nucleus and an α-particle of kinetic energy of 5×10^6 electron volts. The process which will give the greatest amount of

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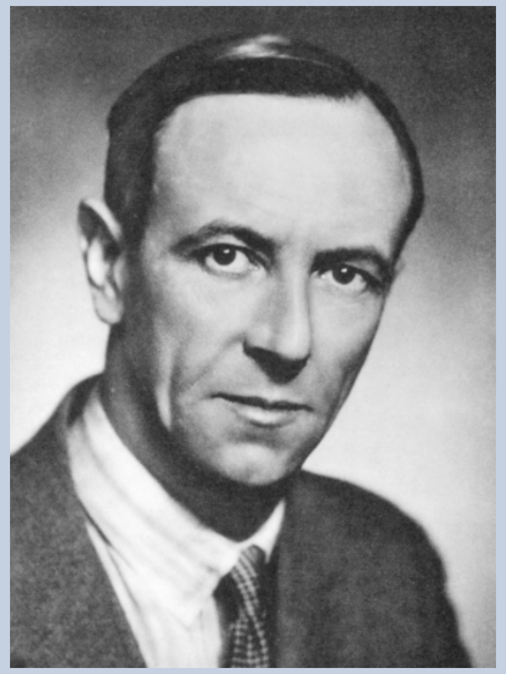

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The experimental results were very difficult to explain on the hypothesis that the beryllium radiation was a quantum radiation, but followed immediately if it were supposed that the radiation consisted of particles of mass nearly equal to that of a proton and with no net charge, or neutrons. A short state-

To study the radiation: ionisation chamber connected to a valve amplifier placed after a 2 mm-thick paraffin wax sheet

Polonium source from a solution of radium →

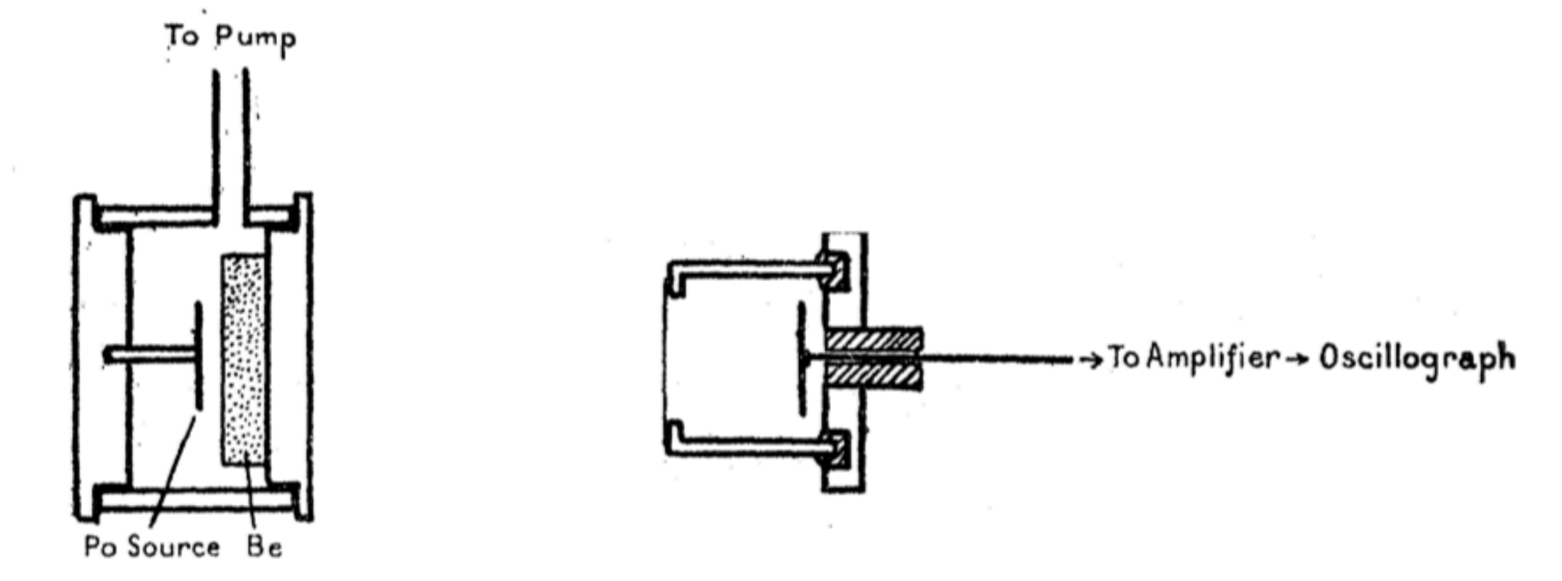

FIG. 1.

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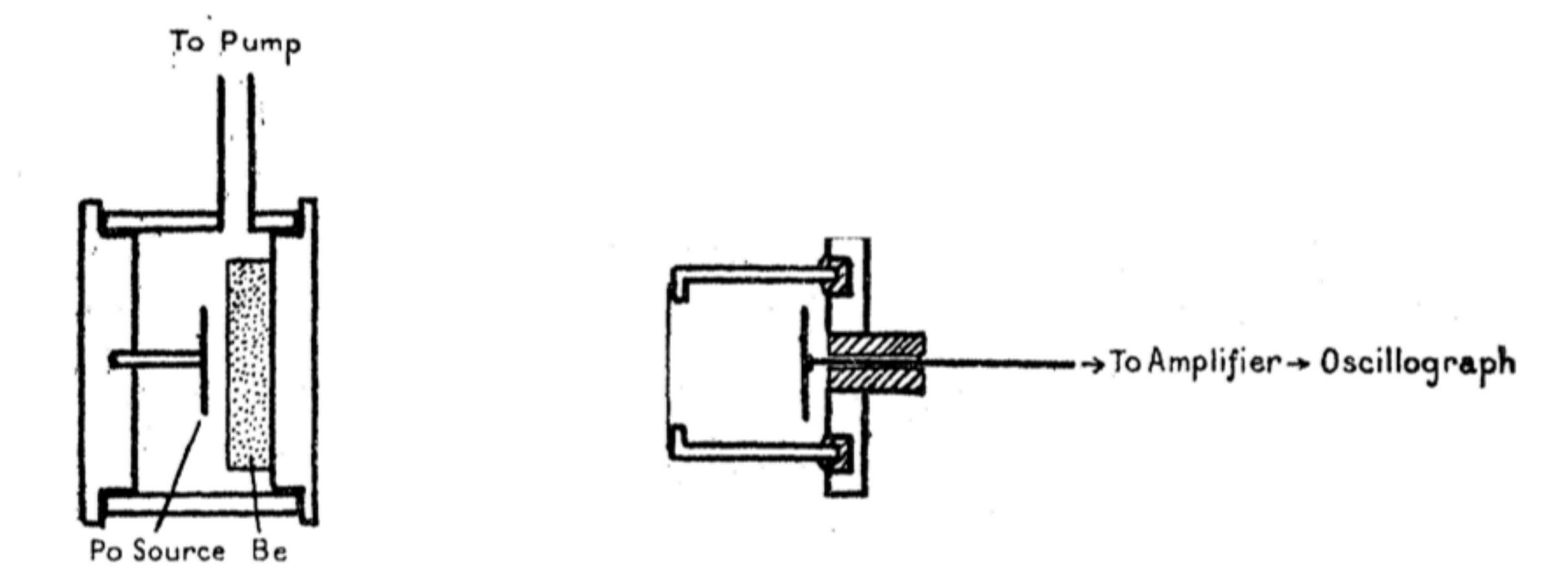

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← Ionisation chamber

Absorption curves of the Beryllium radiation shows that they are proton:
Aluminium foil placed between the paraffin and the chamber

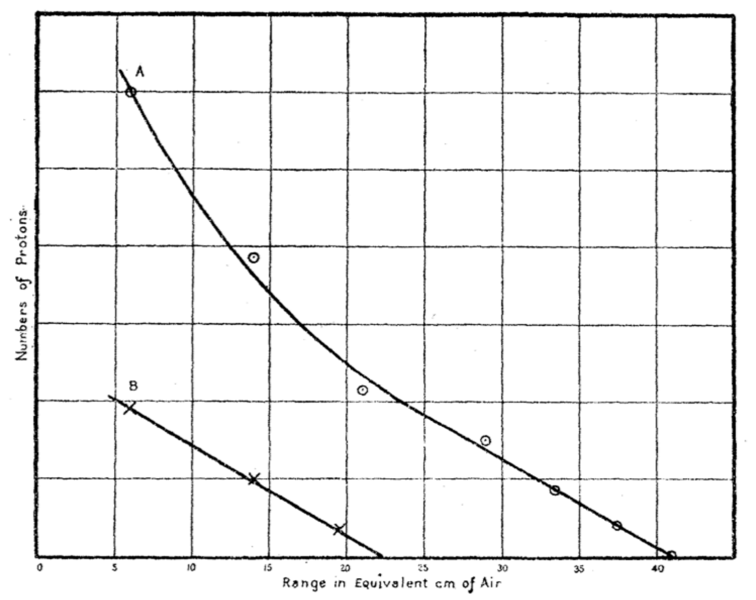

Fig. 2.

The neutron discovery: Chadwick's experiment (1932)

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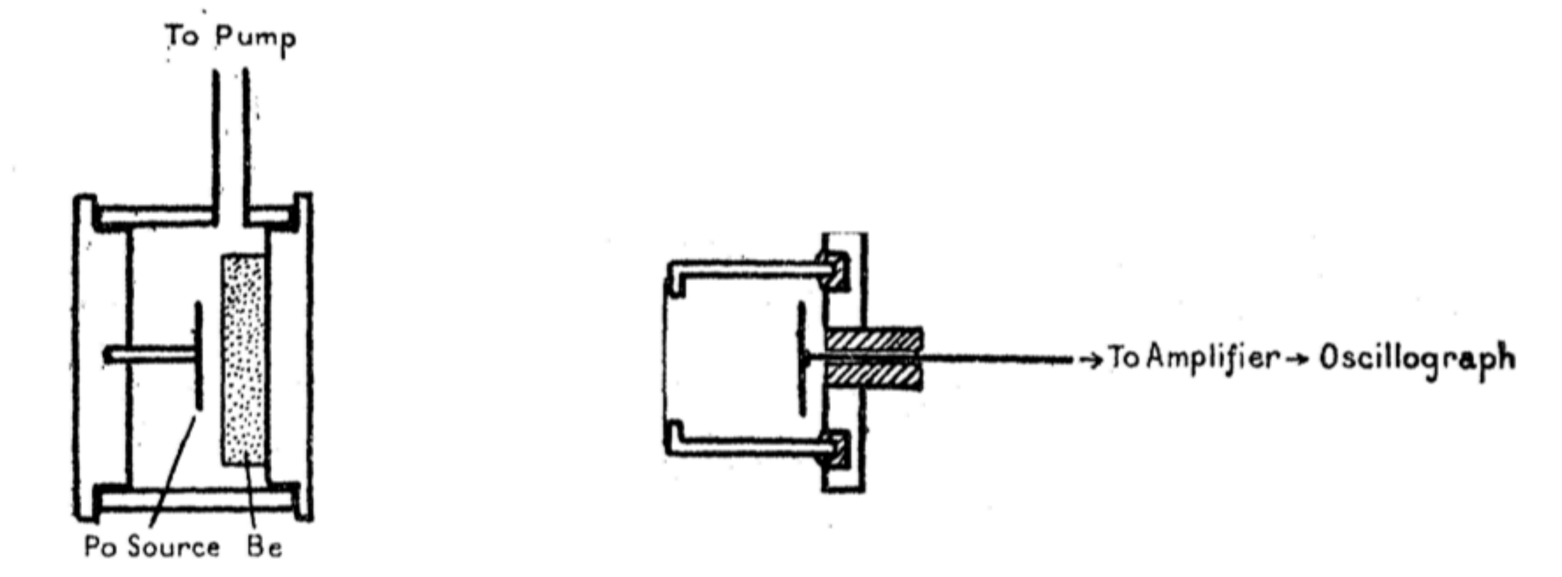

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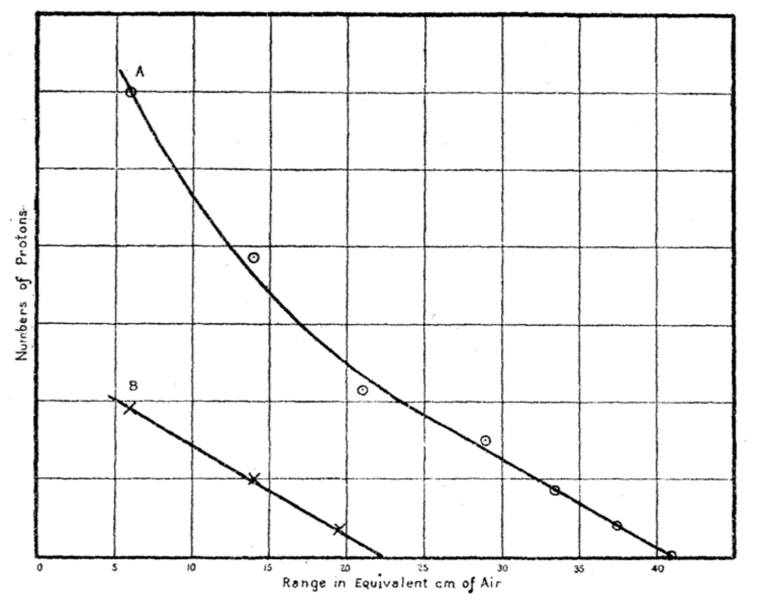

FIG. 2.

Studied gold, lithium, beryllium, boron, carbon and nitrogen foil in front of the chamber

Studied different gases in the chamber: hydrogen, helium, nitrogen, oxygen and argon

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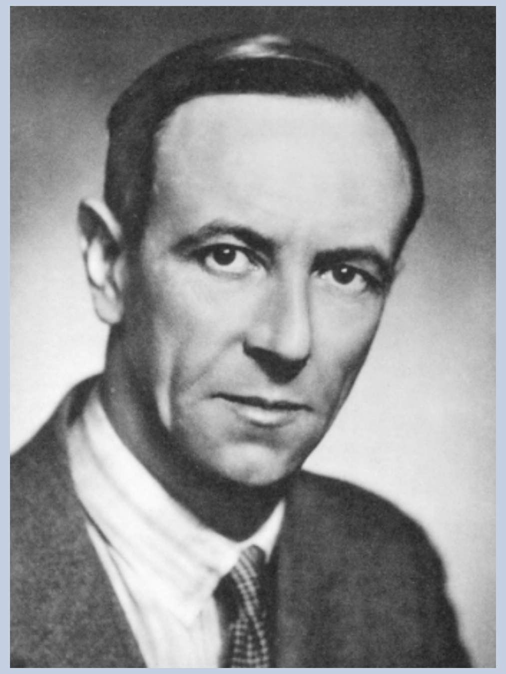

Assume the process is: $B^{11} + He^4 \rightarrow N^{14} + n^1.$

From conservation of energy, reconstruct the mass of the neutron (in atomic mass unit):

The masses are $B^{11} = 11\cdot00825 \pm 0\cdot0016$; $He^4 = 4\cdot00106 \pm 0\cdot0006$; $N^{14} = 14\cdot0042 \pm 0\cdot0028$. The kinetic energies in mass units are α-particle $= 0\cdot00565$; neutron $= 0\cdot0035$; and nitrogen nucleus $= 0\cdot00061$. We find therefore that the mass of the neutron is $1\cdot0067$. The errors quoted for the

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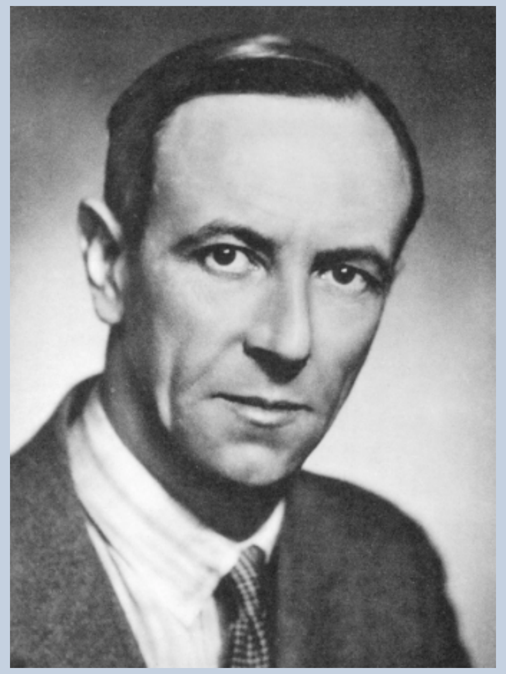

Assume the process is: $B^{11} + He^4 \rightarrow N^{14} + n^1.$

From conservation of energy, reconstruct the mass of the neutron (in atomic mass unit):

The masses are $B^{11} = 11 \cdot 00825 \pm 0 \cdot 0016$; $He^4 = 4 \cdot 00106 \pm 0 \cdot 0006$; $N^{14} = 14 \cdot 0042 \pm 0 \cdot 0028$. The kinetic energies in mass units are α-particle $= 0 \cdot 00565$; neutron $= 0 \cdot 0035$; and nitrogen nucleus $= 0 \cdot 00061$. We find therefore that the mass of the neutron is $1 \cdot 0067$. The errors quoted for the

(Wrong) Interpretation:

Such a value for the mass of the neutron is to be expected if the neutron consists of a proton and an electron, and it lends strong support to this view.


THANKS