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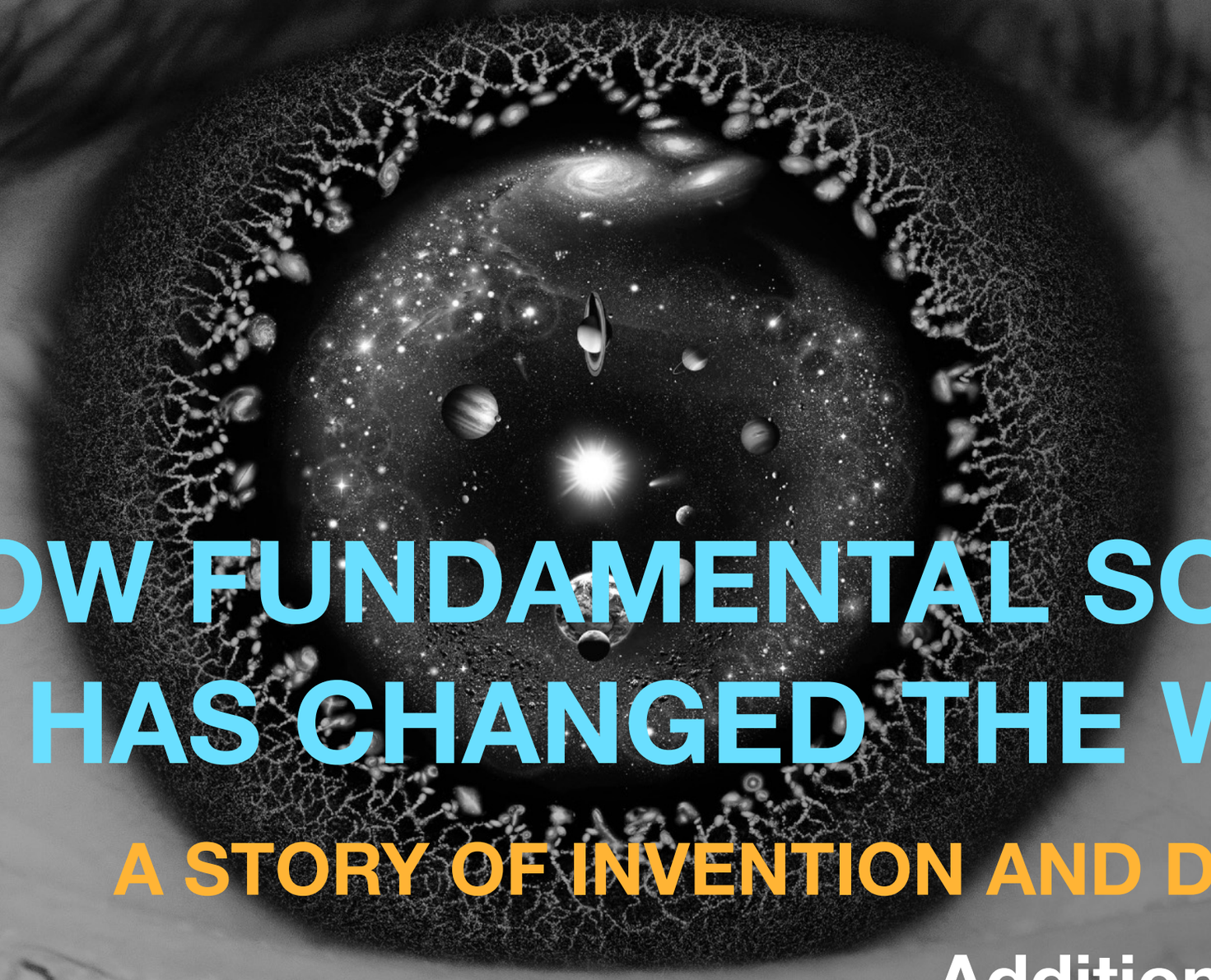


HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

Additional Material

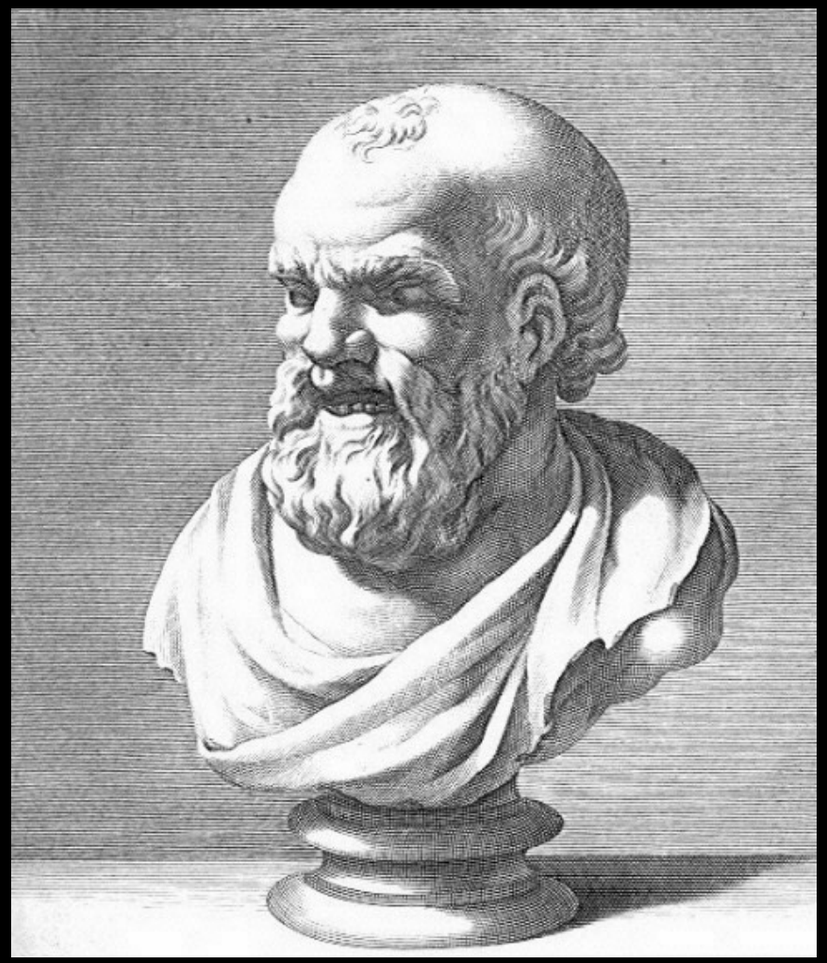
Philipp Windischhofer

November 11, 2023

Composite image created by combining representation of universe sphere by Pablo Carlos Budassi with human eye by Kamil Saitov (Google Commons).

Is matter continuous or discrete?

A topic of "eternal" philosophical debate!



Democritus *(ca. 300 BC):*

"By convention there is sweetness,
by convention there is bitterness,
by convention there is color;
in reality only atoms and the void."

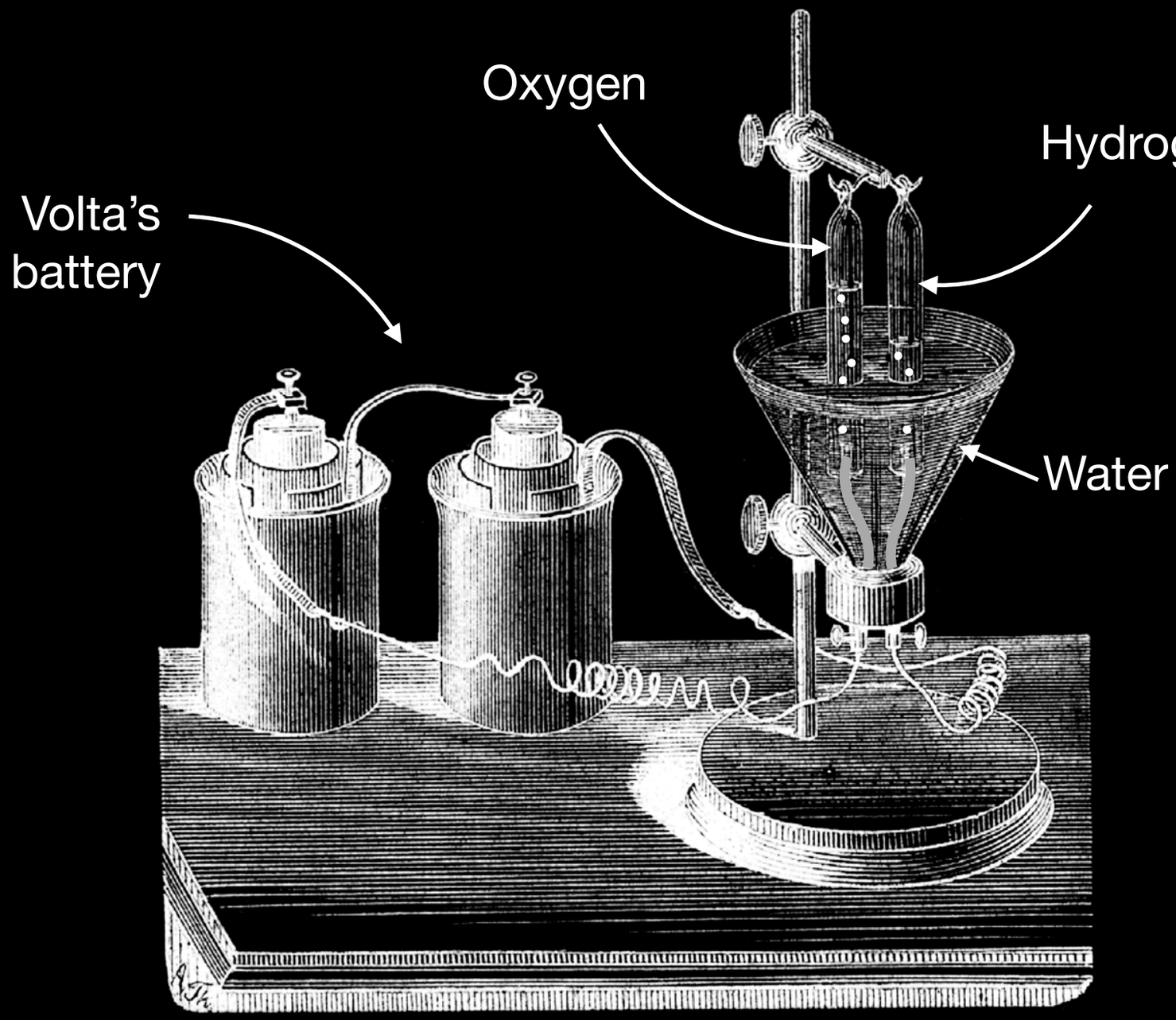
"Bitterness is caused by small, angular,
jagged atoms passing across the tongue."

"Sweetness is caused by larger, smoother,
more rounded atoms."

The first *real* hints: Chemistry

Splitting substances with electricity

Water → Hydrogen + Oxygen



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The first *real* hints: Chemistry

Recombining substances

"When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam."

Hydrogen + Oxygen → Water

John Dalton

Carbon *100g* + **Oxygen** *133g* → **Carbon monoxide**

2:1

Carbon *100g* + **Oxygen** *266g* → **Carbon dioxide**

***"Law of multiple proportions"* (1804)**

Such ratios will always involve whole numbers!

Dalton's atoms (1808)

"In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance."

1 atom of A + 1 atom of B = 1 atom of C
1 atom of A + 2 atoms of B = 1 atom of D

"Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7."

Wrong! It's 1:16!

1) Atoms are elementary

2) As such, they only come in whole numbers

3) The masses of different atoms relate to each other as whole numbers

Dalton's atoms (1808)

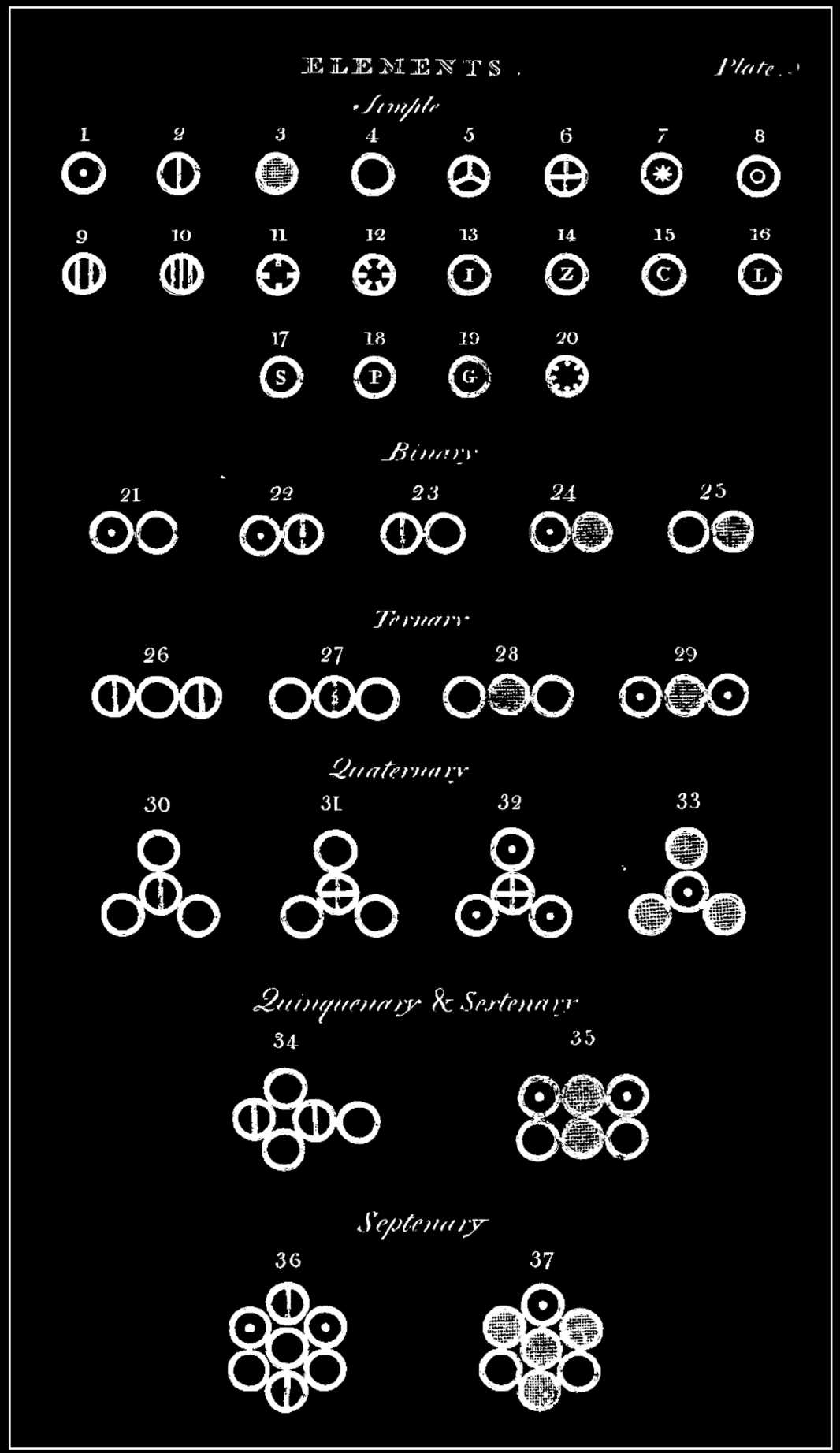
Table of relative atomic weights:

Fig.			Fig.		
1	Hydrog. its rel. weight	1	11	Strontites	46
2	Azote	5	12	Barytes	68
3	Carbone or charcoal...	5	13	Iron	38
4	Oxygen	7	14	Zinc	56
5	Phosphorus	9	15	Copper	56
6	Sulphur	13	16	Lead	95
7	Magnesia	20	17	Silver	100
8	Lime	23	18	Platina	100
9	Soda	28	19	Gold	140
10	Potash	42	20	Mercury	167

Some are close, but most are wrong!

On the nature of atoms:

"The atoms of such bodies are conceived at present to be simple."

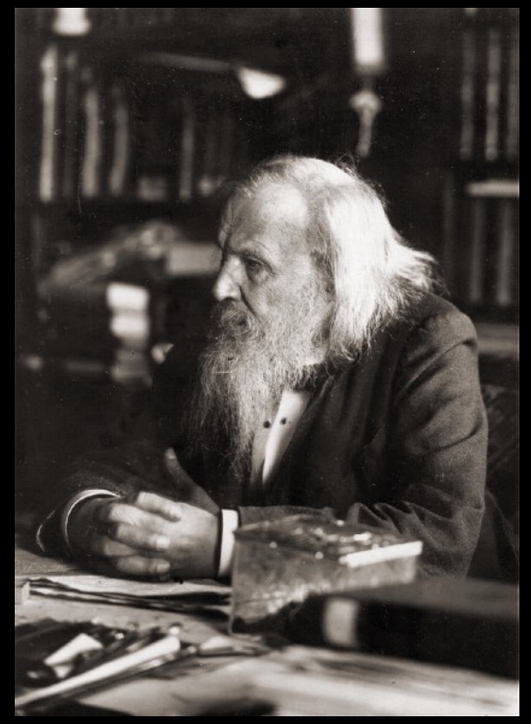


Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

Is there any order in this chaos?

Apparent periodicity! Missing elements!



Dmitri Mendeleev

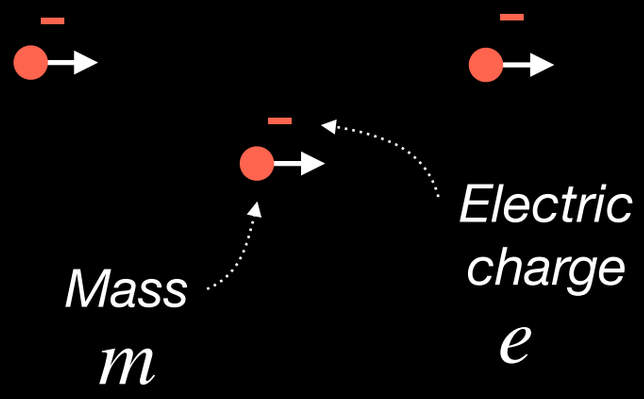
Eight groups of chemically similar elements

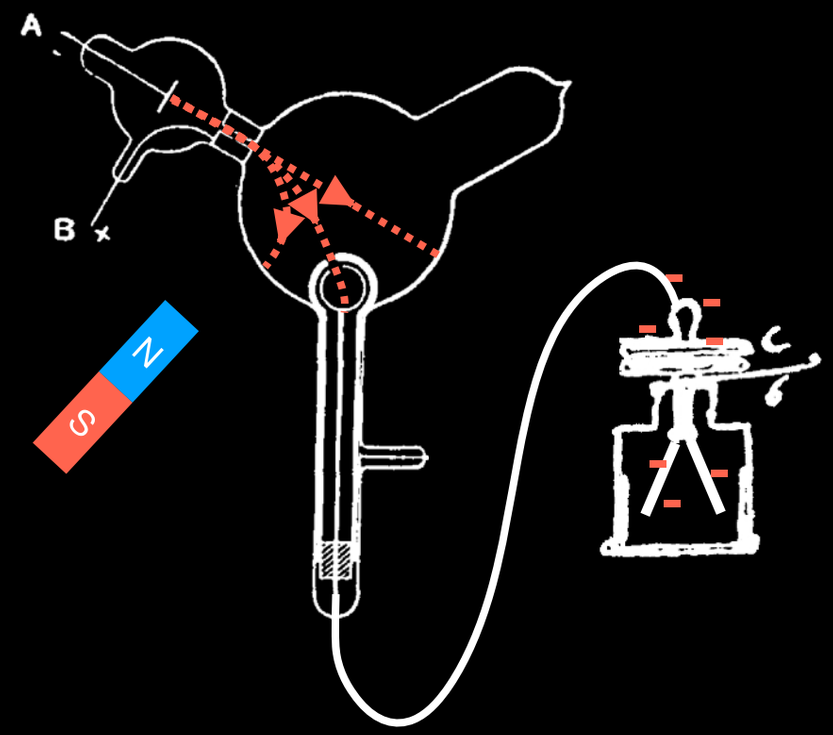
Reihen	Gruppe I. — R^1O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=86	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev's table *(1871)*

Back to Thomson

A stream of electrons



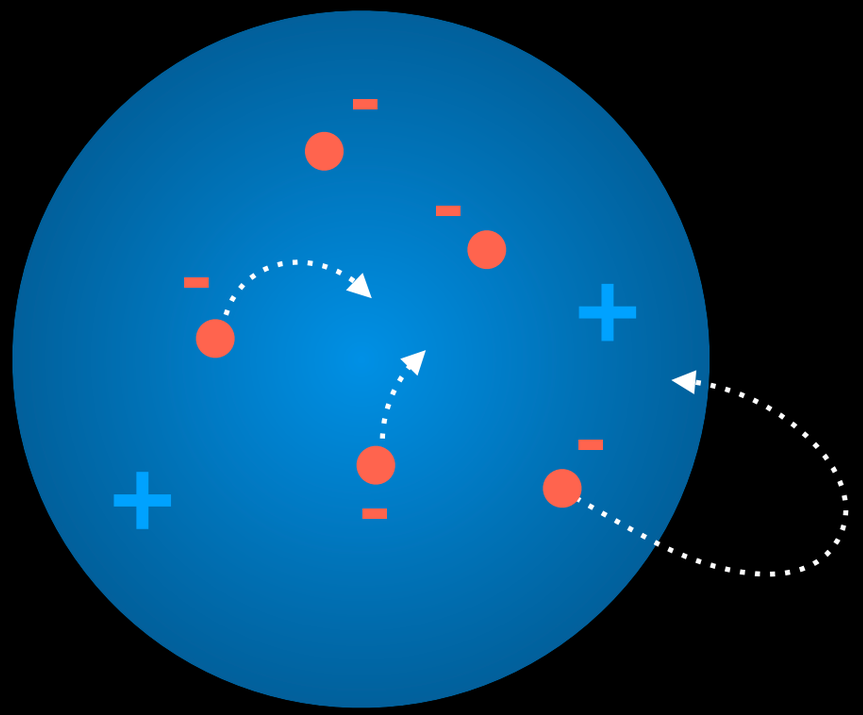


"Thus on this view, we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state."

Thomson’s view of the atom (1904)

Normal matter is electrically neutral

→ Atoms are electrically neutral

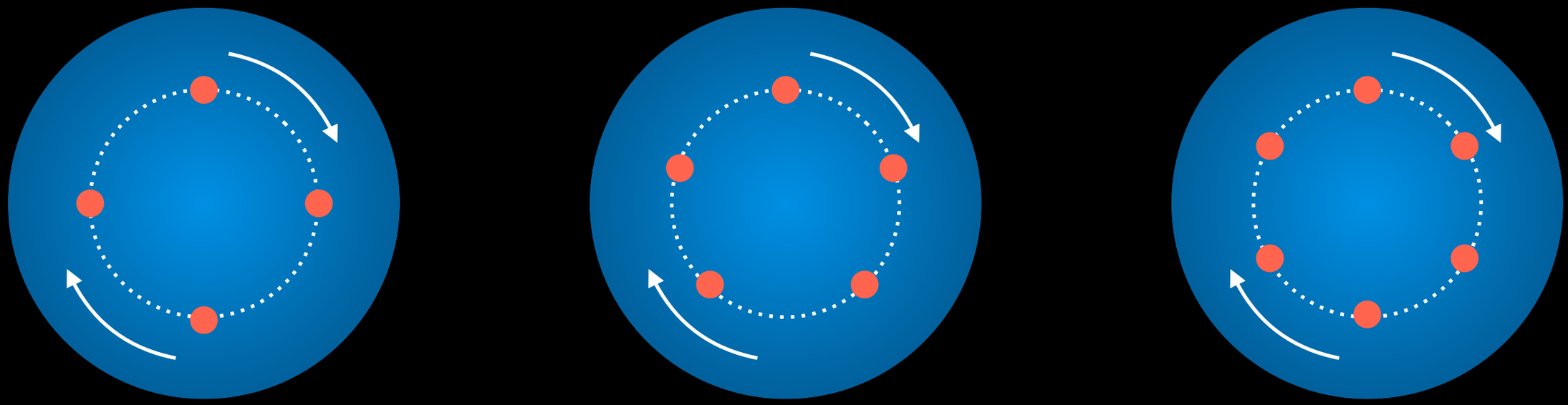


“We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification.”

Thomson's view of the atom (1904)

"What properties would this structure confer upon the atom?"

"[Stability] suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere."

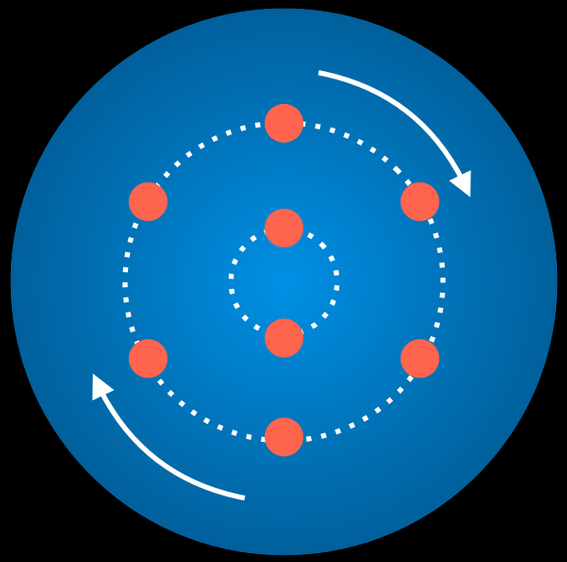


"A large number of particles cannot be in a stable equilibrium when arranged as a single ring."

"It can be made stable by placing inside it an appropriate number of corpuscles."

Thomson’s view of the atom (1904)

“It can be made stable by placing inside it an appropriate number of corpuscles.”



“Shells”

What would be the chemical properties of such atoms?

“The group containing 60 corpuscles would be the most electropositive of the series …”

Can the laws of mechanics explain chemistry?

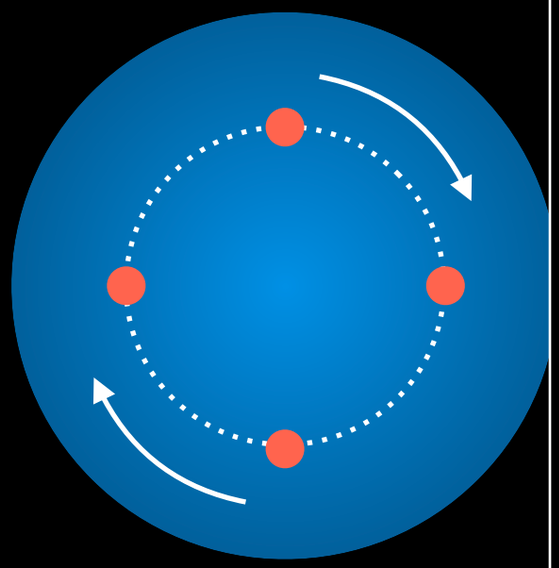
Thomson's view of the atom (1904)

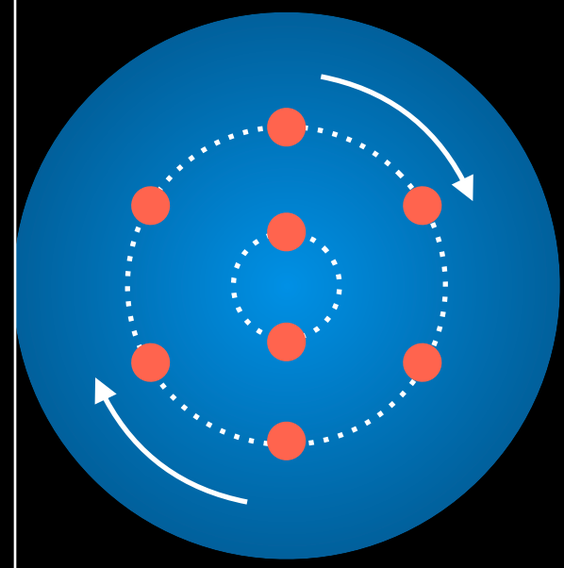
Adding

"Plum Pudding model"

Electrons are like raisins in a cake!

jumps!)



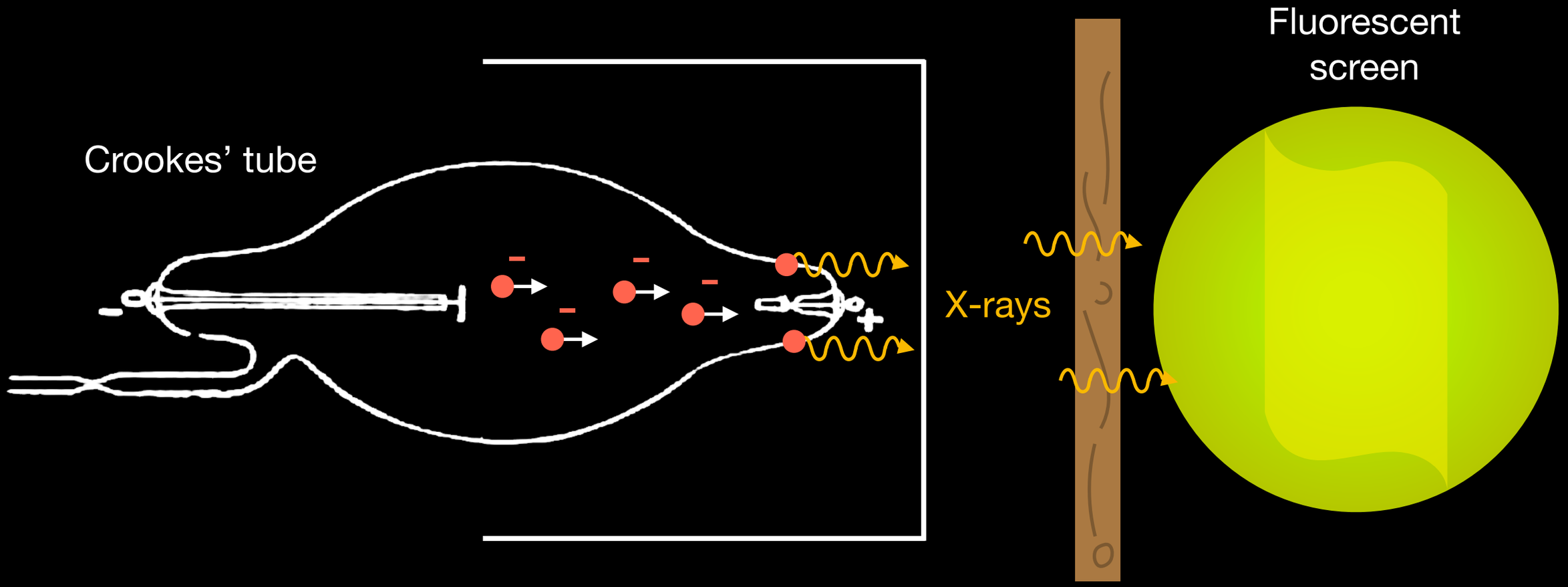


The first and last element in each of these series has no valency, the second is a monovalent electropositive element, the last but one is a monovalent electronegative element, the third is a divalent electropositive element, the last but two a divalent electronegative element, and so on.

How to look inside the atom?

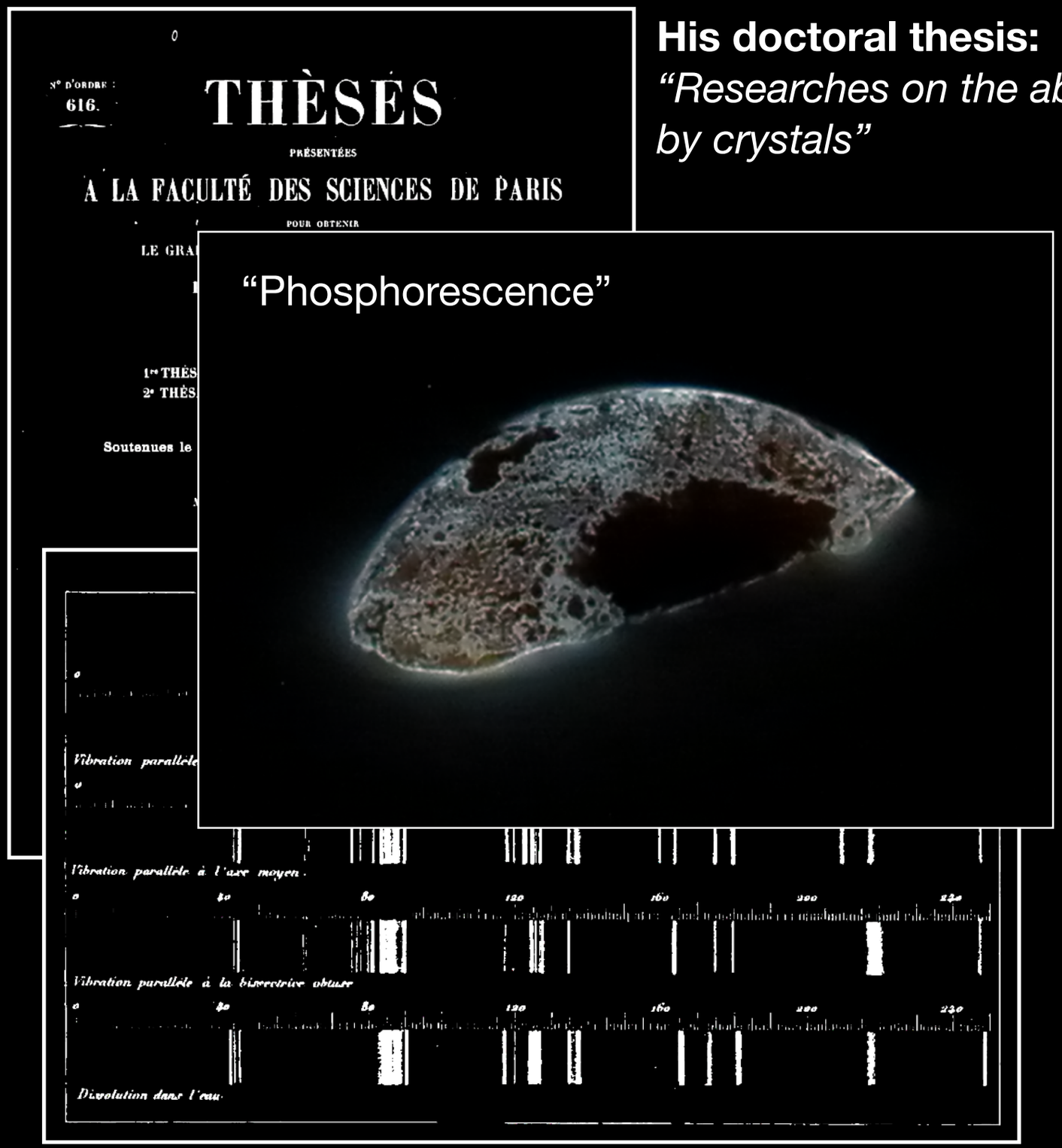
Back ten years to Röntgen and his X-rays …

Röntgen’s big discovery



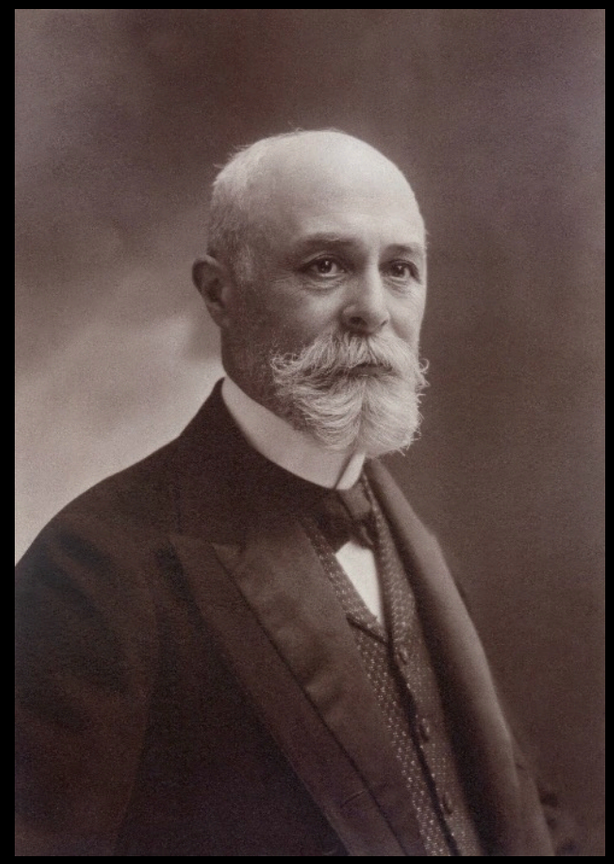
Used widely-available equipment → *surge of interest from other scientists*

Henri Becquerel

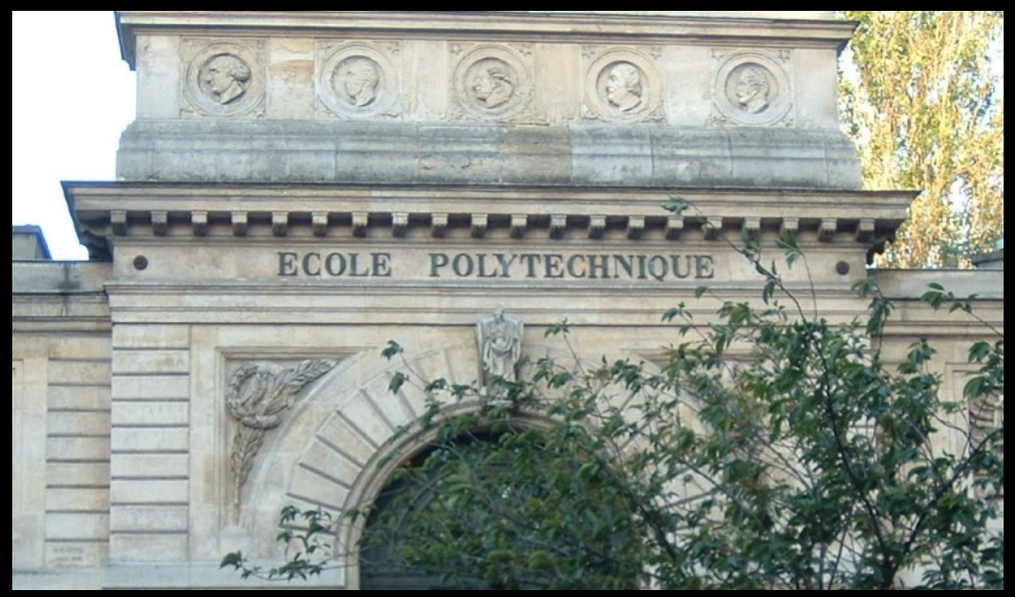


His doctoral thesis:
"Researches on the absorption of light by crystals"

"Phosphorescence"



1895: Professor at Ecole Polytechnique
(Ca. 80 years after Sadi Carnot)



Phosphorescence and uranium

White phosphorus also glows in the dark!

Ura glow
to sunlight … in the dark for a certain time

“Phosphorescence”

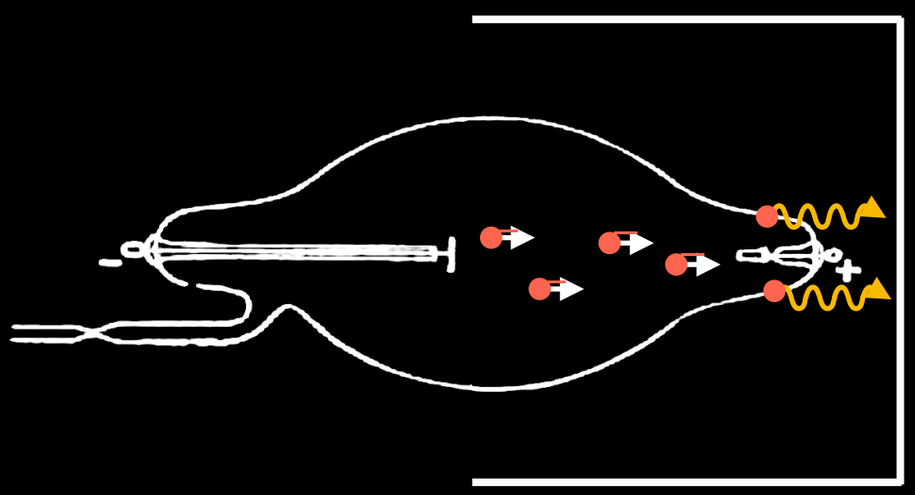
At the Academy of Sciences in 1896

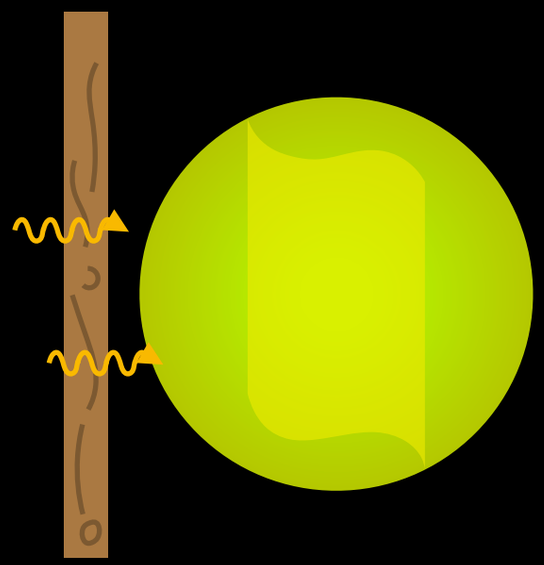
“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

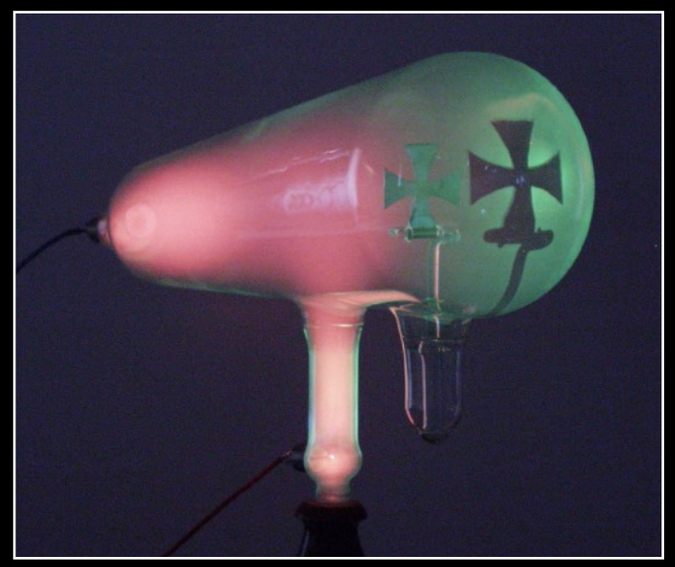
“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”

“I was answered that the origin of the radiation was the luminous spot of the wall of the tube that received the cathodic flux.”

“I cogitated at once to search whether the new emission was a manifestation of the phenomenon that gave birth to the phosphorescence and whether all phosphorescent bodies emit similar rays.”





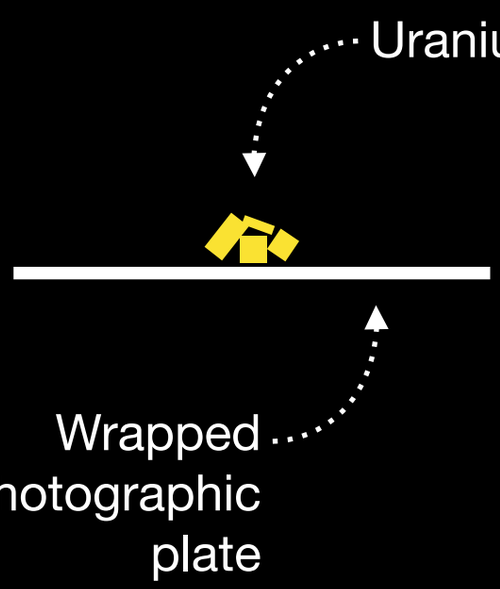


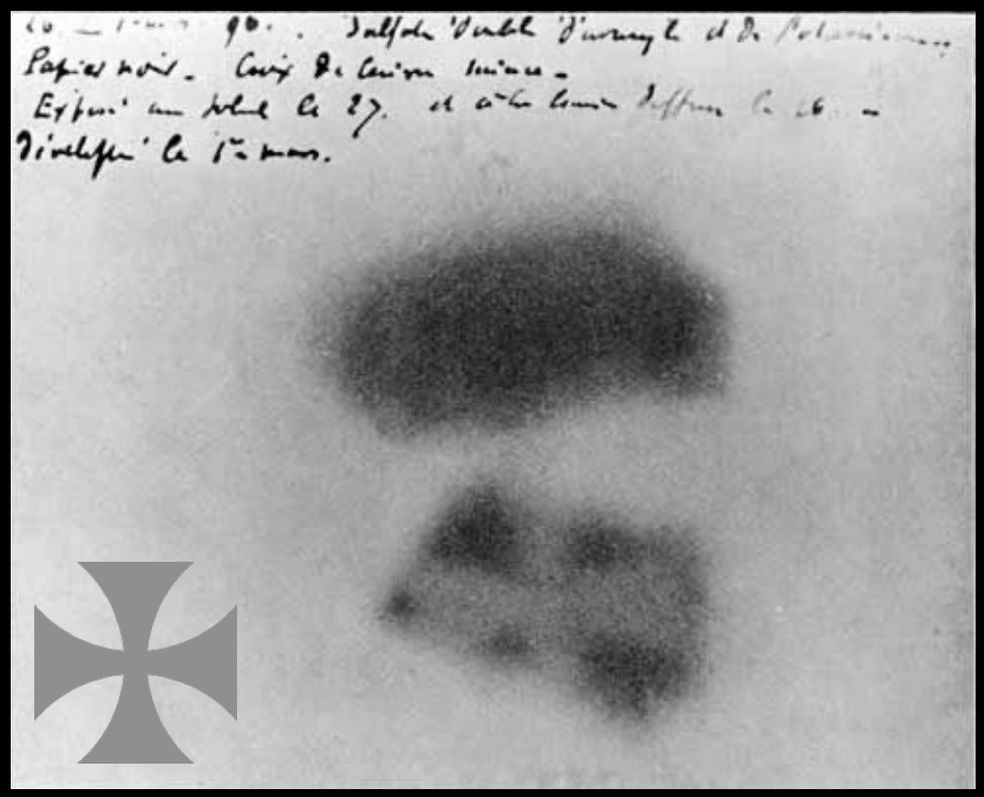
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

[source]

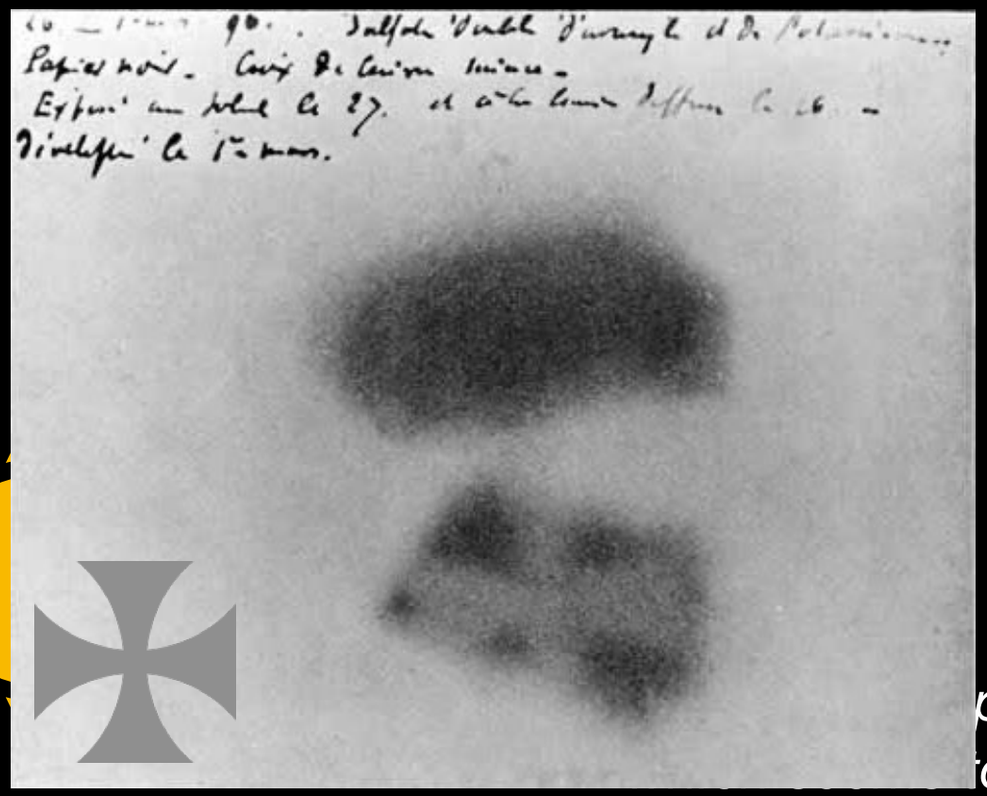
“After developing the photographic plate in the usual way, one observes that the silhouette of the crystalline crust appears in black on the sensitive plate.”





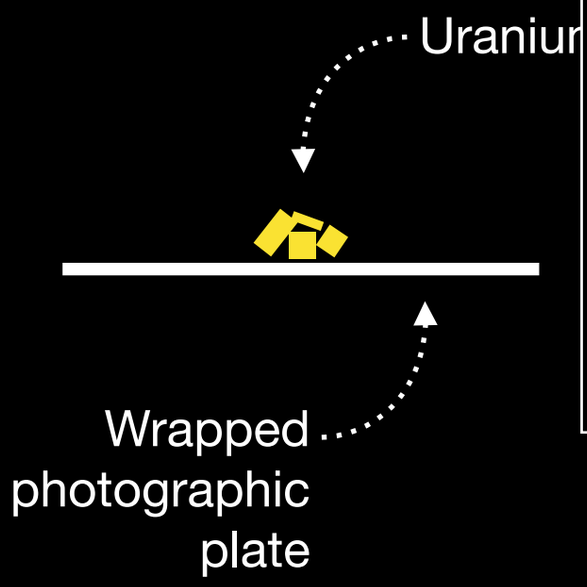
A chance discovery

“A Lumière plate of black cloth.”



[source]

particularly upon the following fact, o me quite important and beyond the phenomena which one could expect to observe.”



“These effects have a great similarity to the effects produced by the rays studied by Mr. Röntgen.”

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It’s not about the sun nor phosphorescence at all!

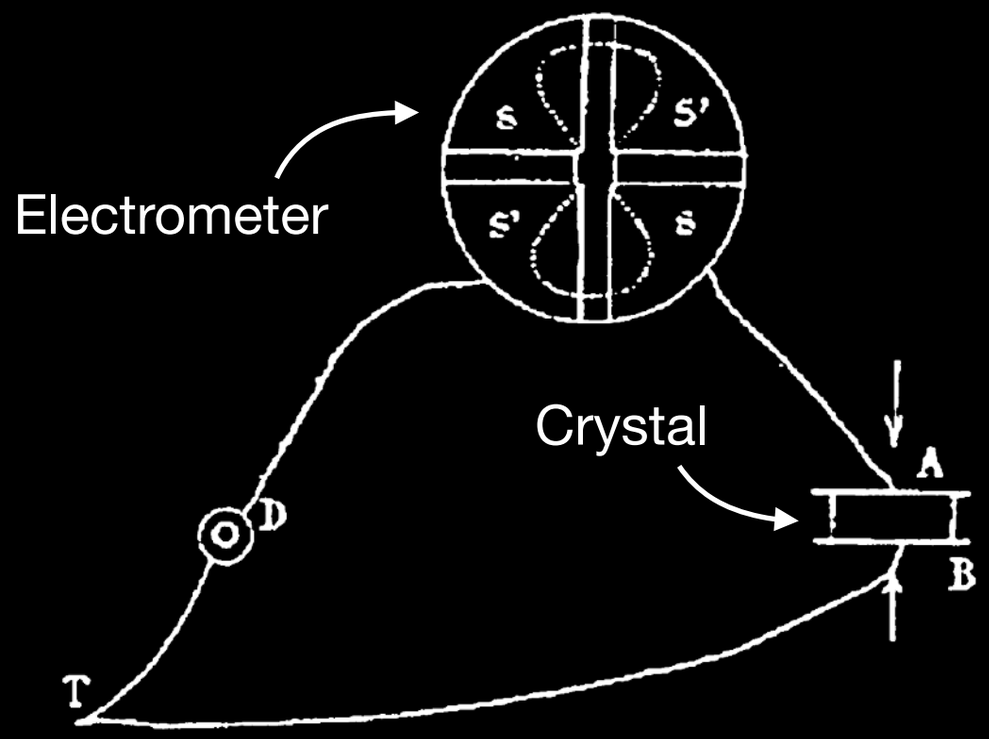
Marie Skłodowska-Curie

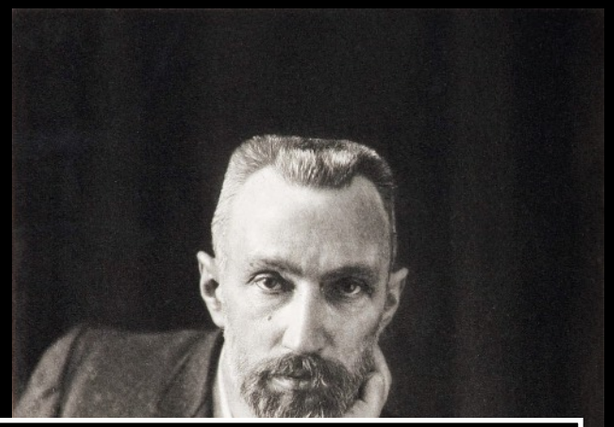
From Poland to Pa
A pact between sist

s i
Vor

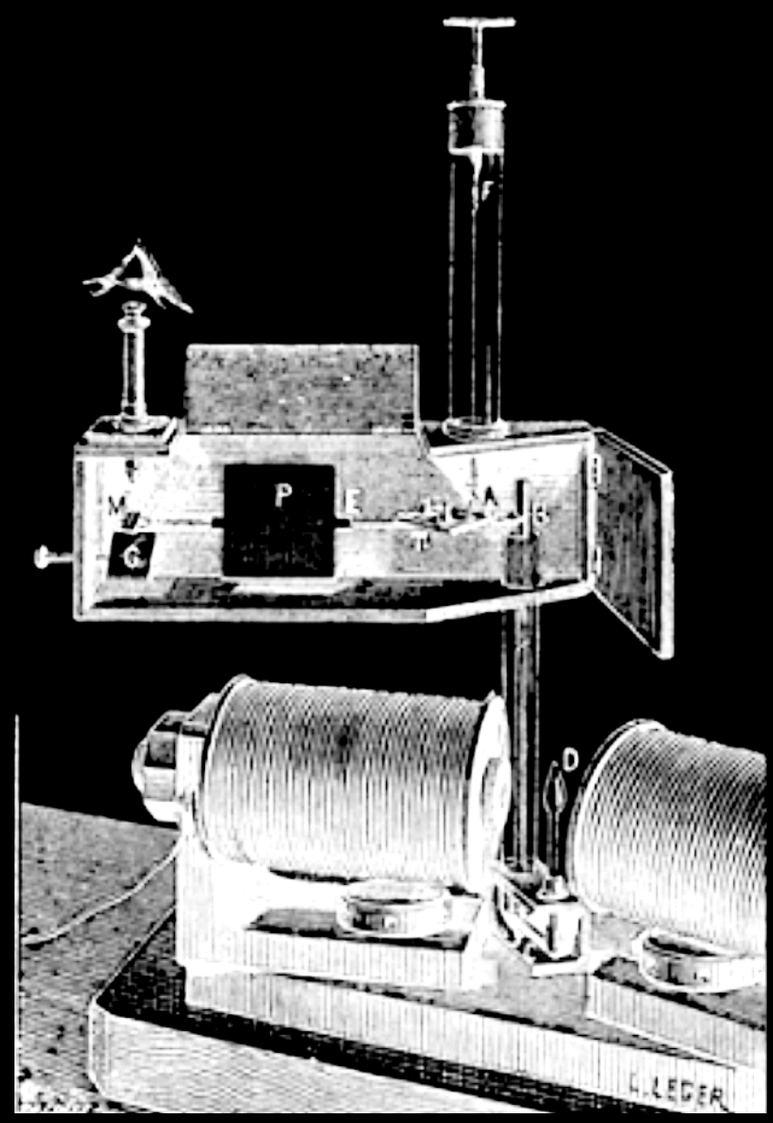
Pierre Curie

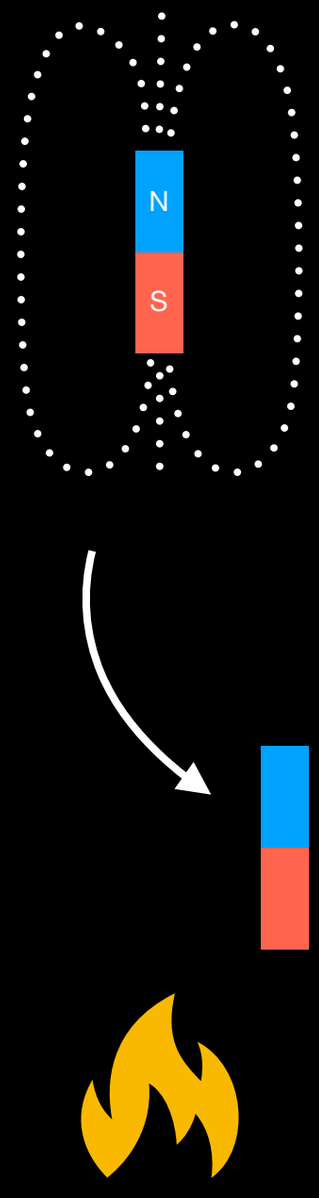
1880: the Curie brothers discover the piezoelectric effect





1895: Magnets lose their magnetism when heated up!

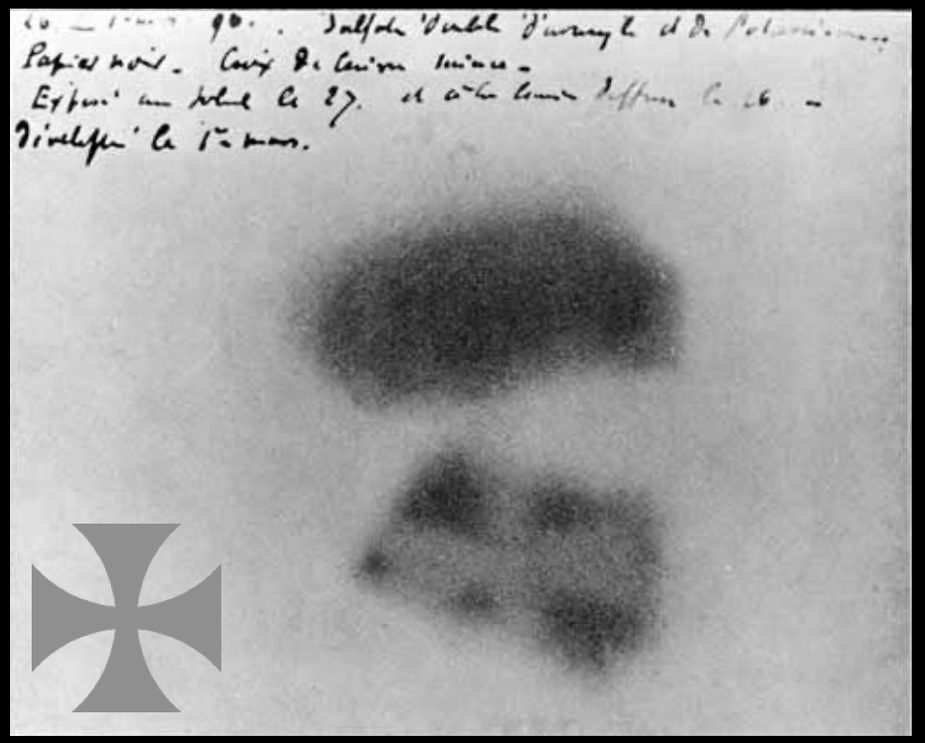




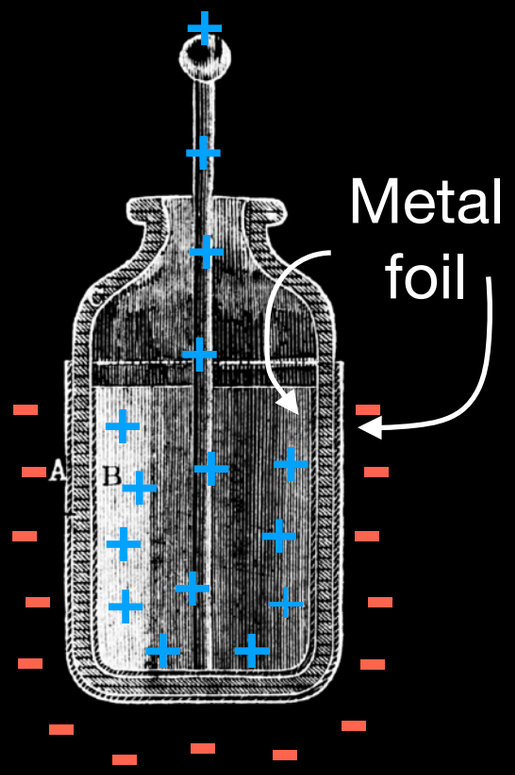
The Curies in 1895

Enjoying their honeymoon (1895)

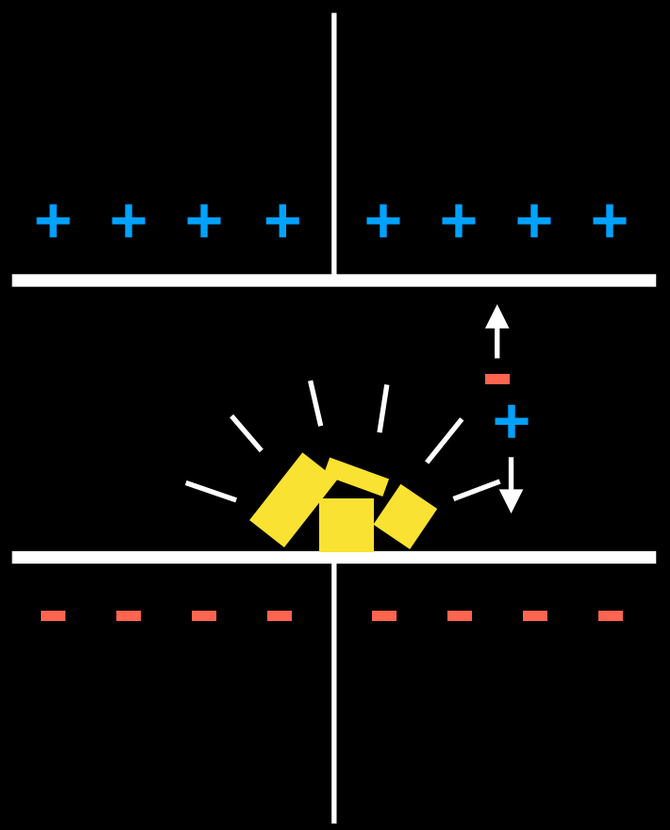
1896: Marie is looking for a doctoral thesis topic



A connection with electricity



Leyden jar
(“Cylindrical condenser”)



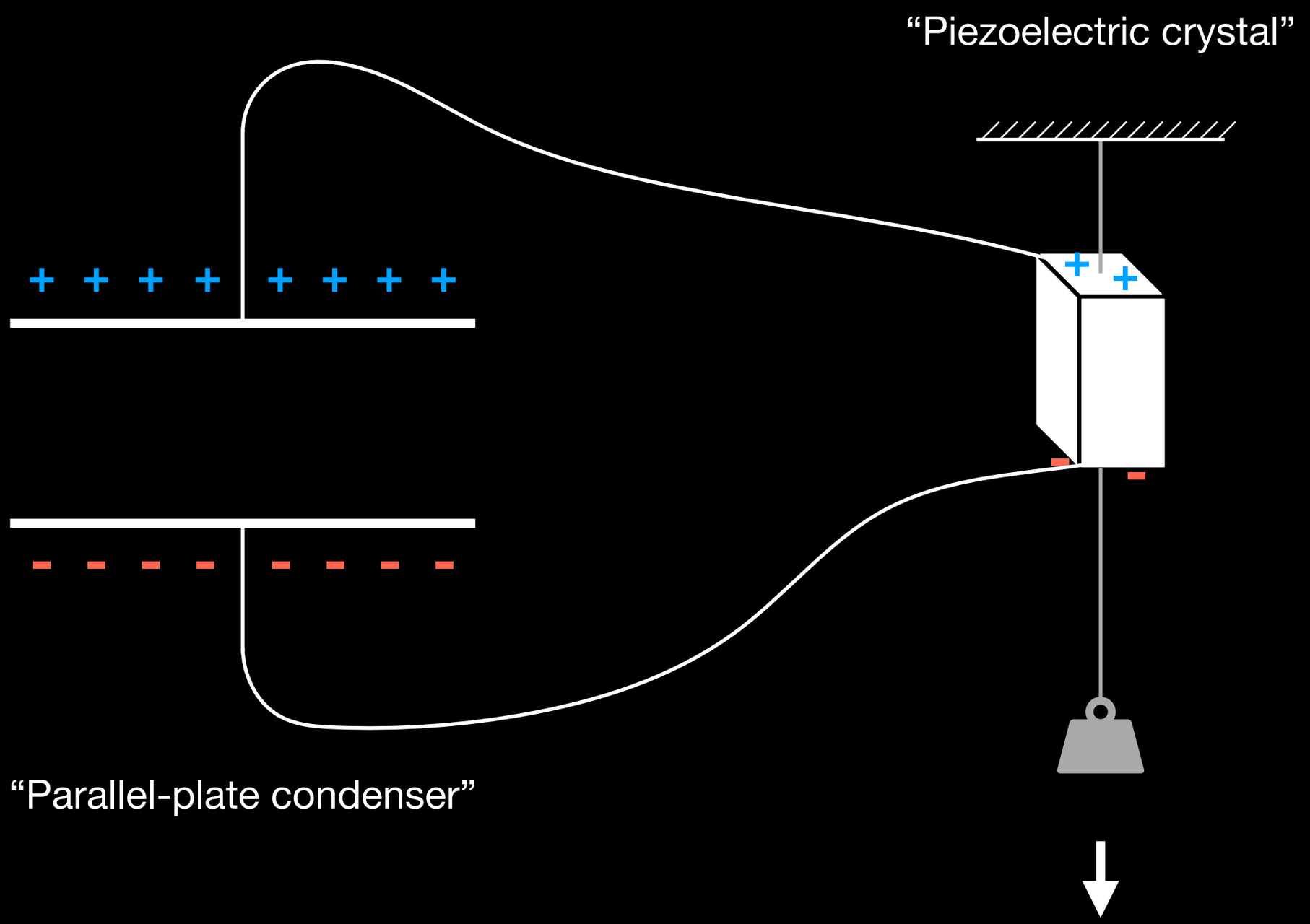
“Becquerel rays”
are “ionizing”

“Parallel-plate condenser”

“Becquerel rays” gradually discharge the condenser

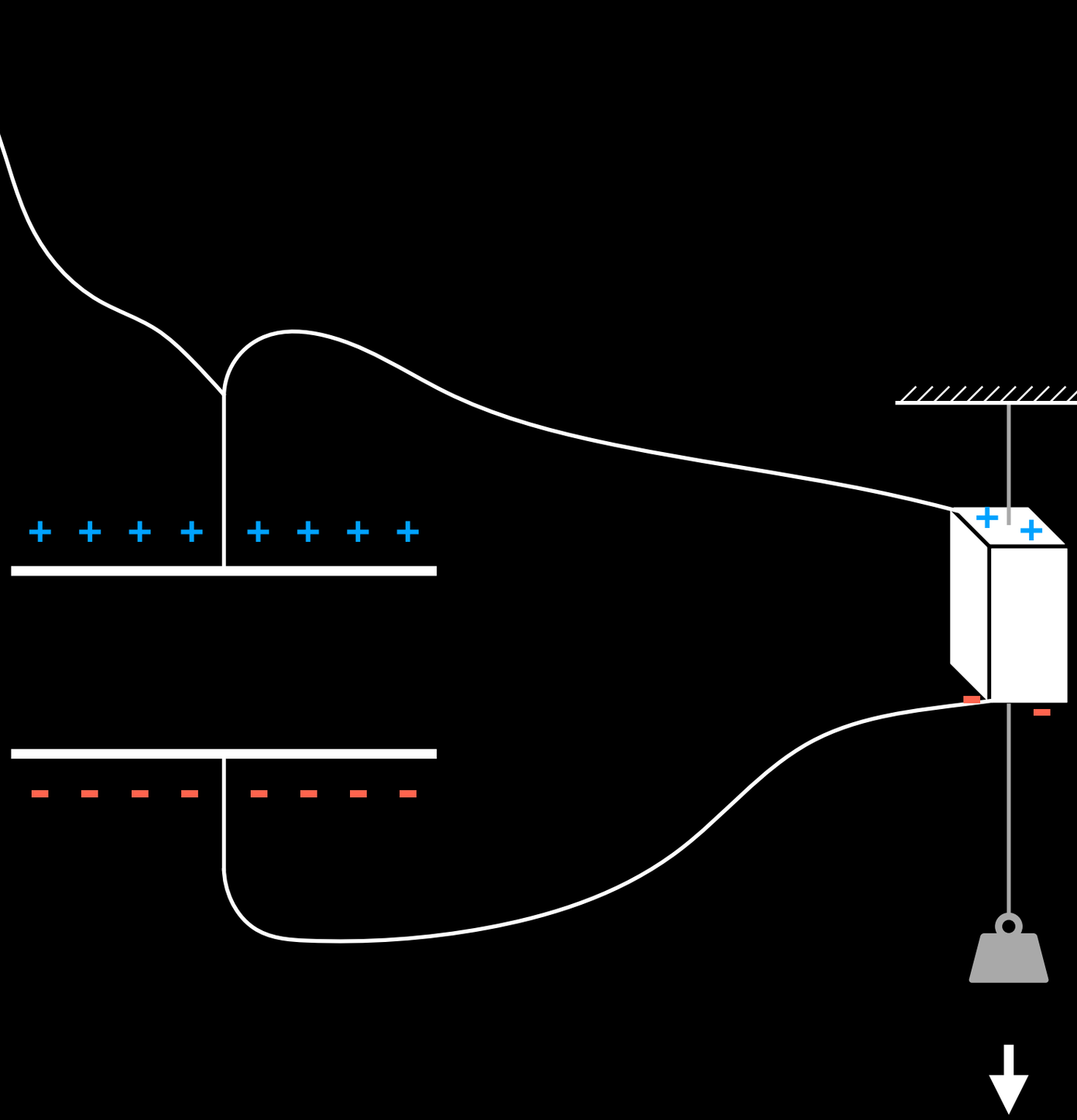
Very small! Need very precise experiments!

How to charge the condenser?

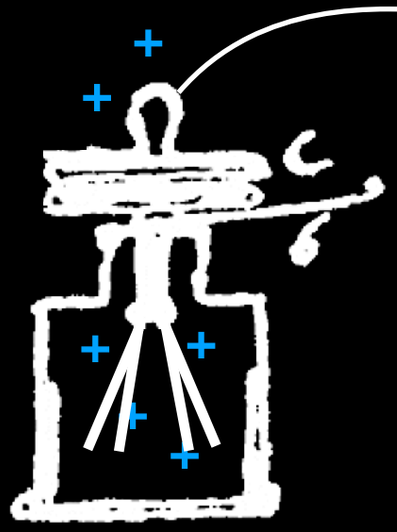


How to measure the discharge?

Electrometer
(Needs to be very sensitive!)



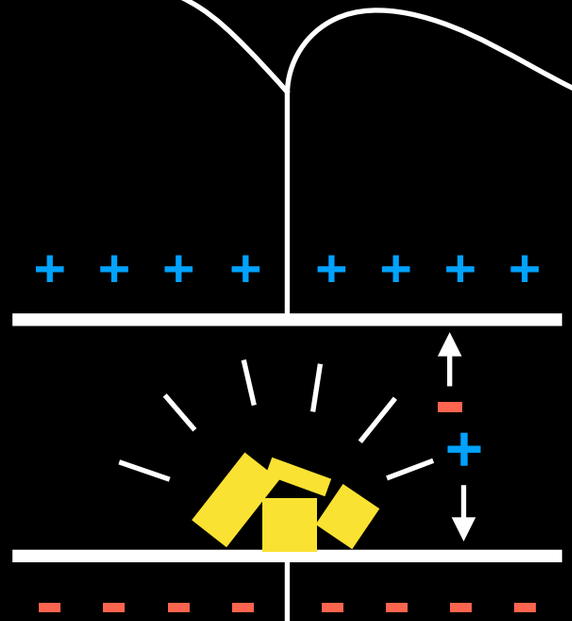
How was the experiment conducted?

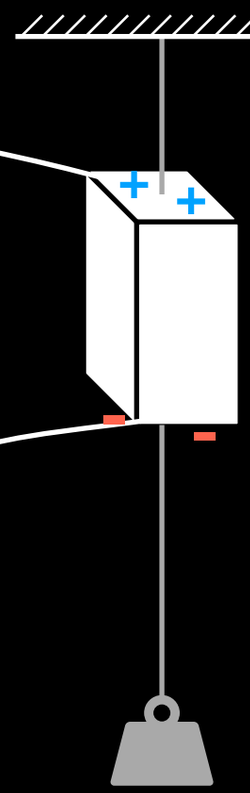


Electrometer
(Needs to be very sensitive!)

1) Put material sample into parallel-plate condenser

2) Wait until discharging condenser reaches specified level





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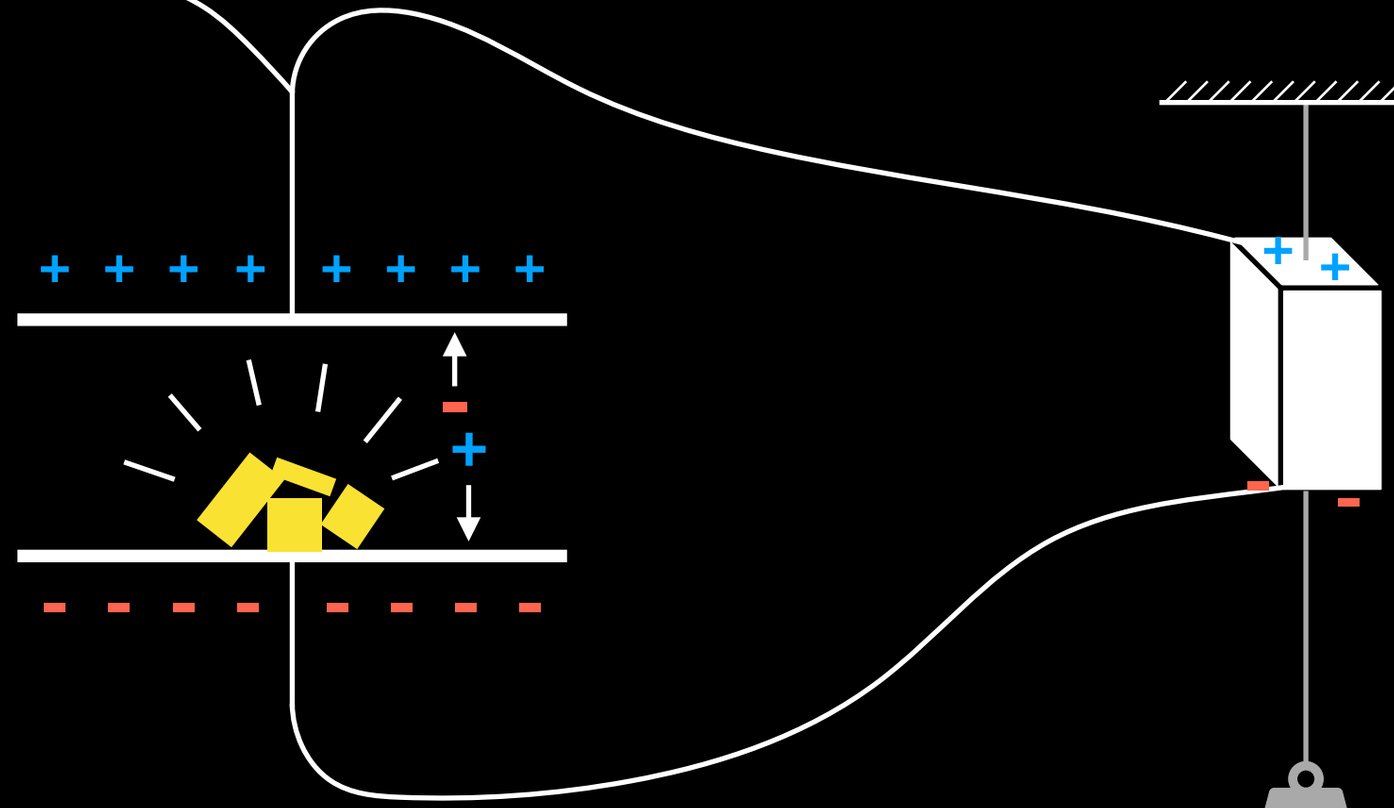


3) Add additional weight to the piezoelectric crystal to recharge condenser to original level

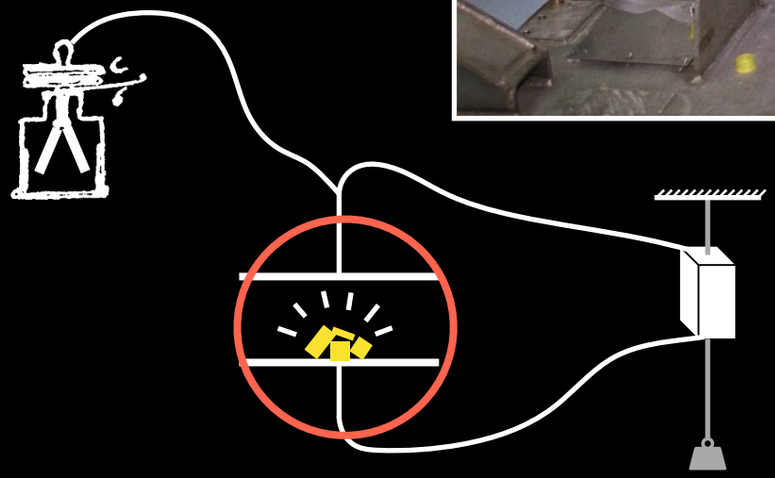
→ Time interval measures strength of radiation

The real experiment

[source]

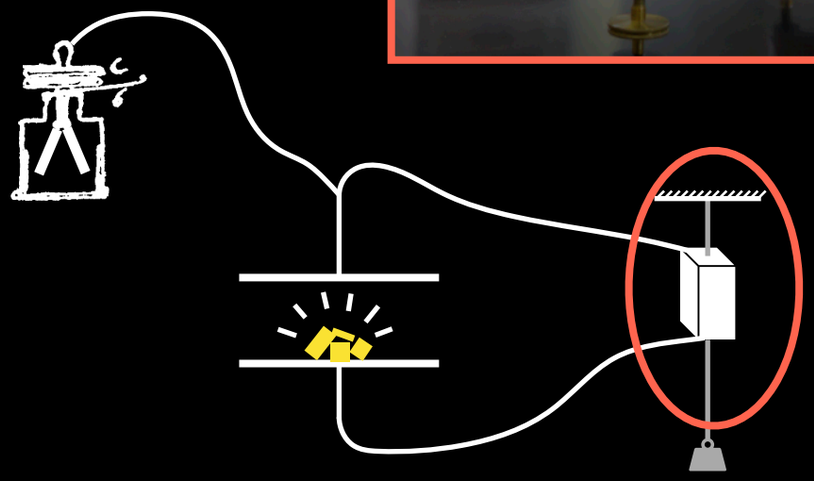
[source]

The real plate condenser

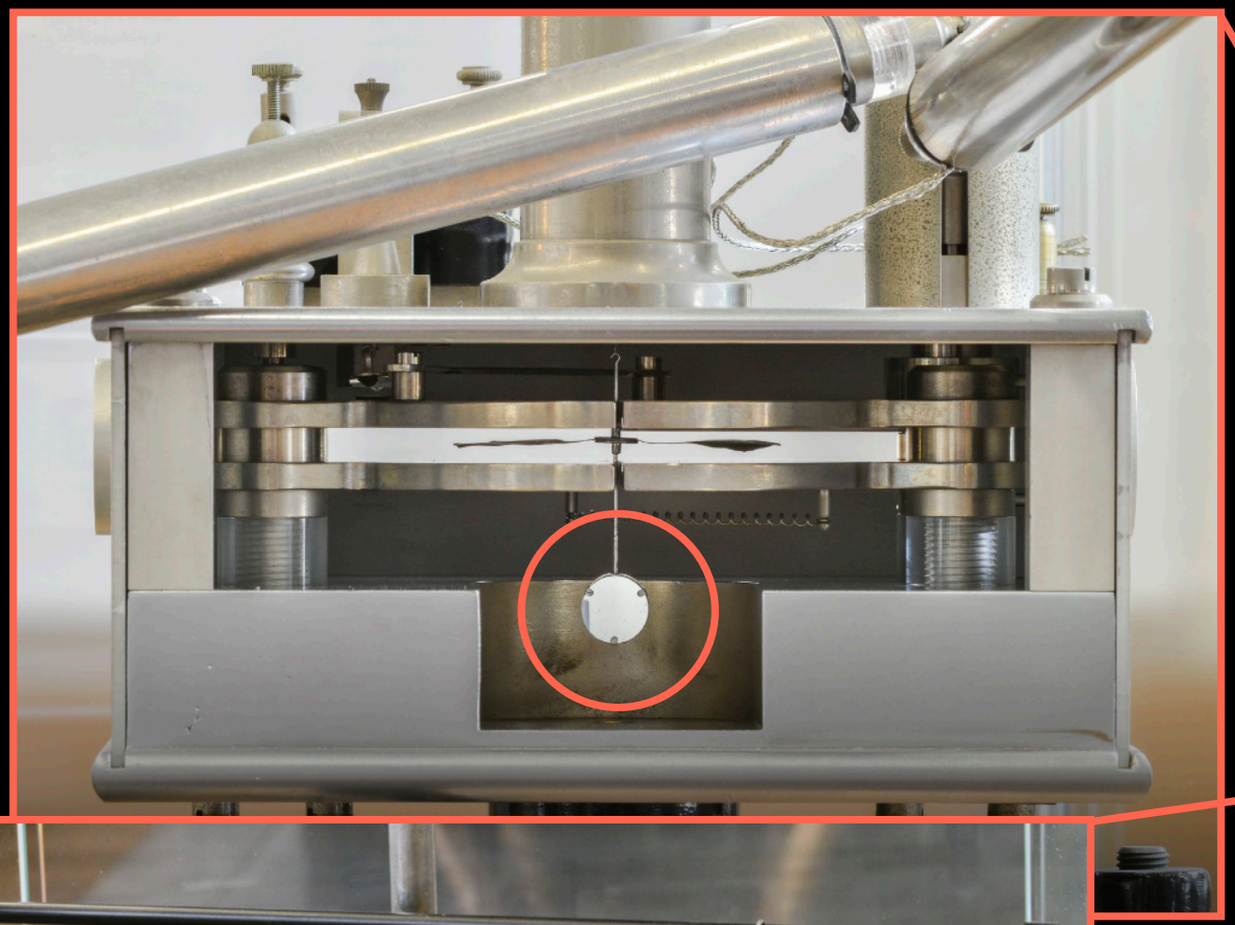


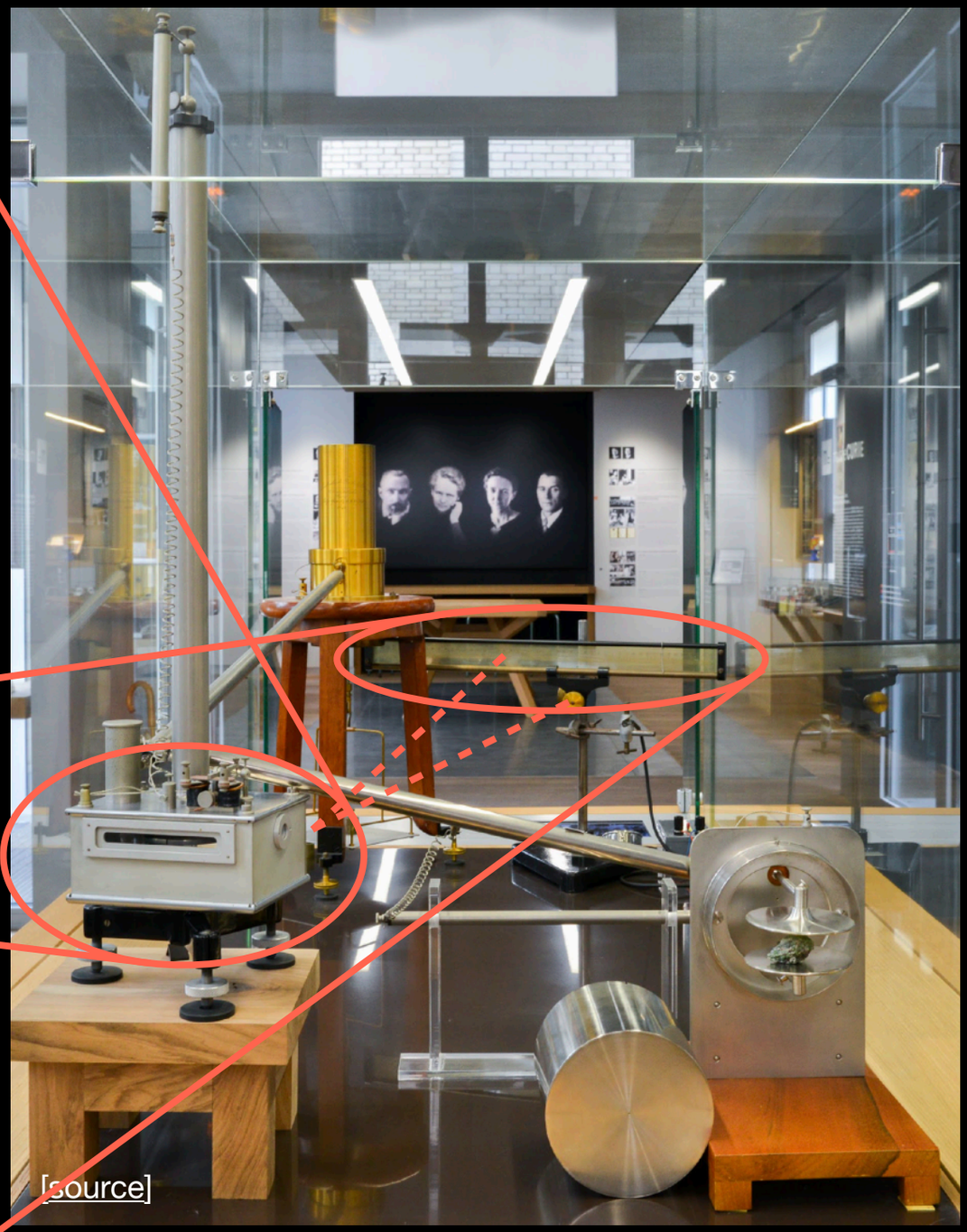
The real piezoelectric crystal

[source]



Pierre’s precision electrometer





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Taking the measurements

Testing different materials

Uranium and thorium minerals are the most “active”

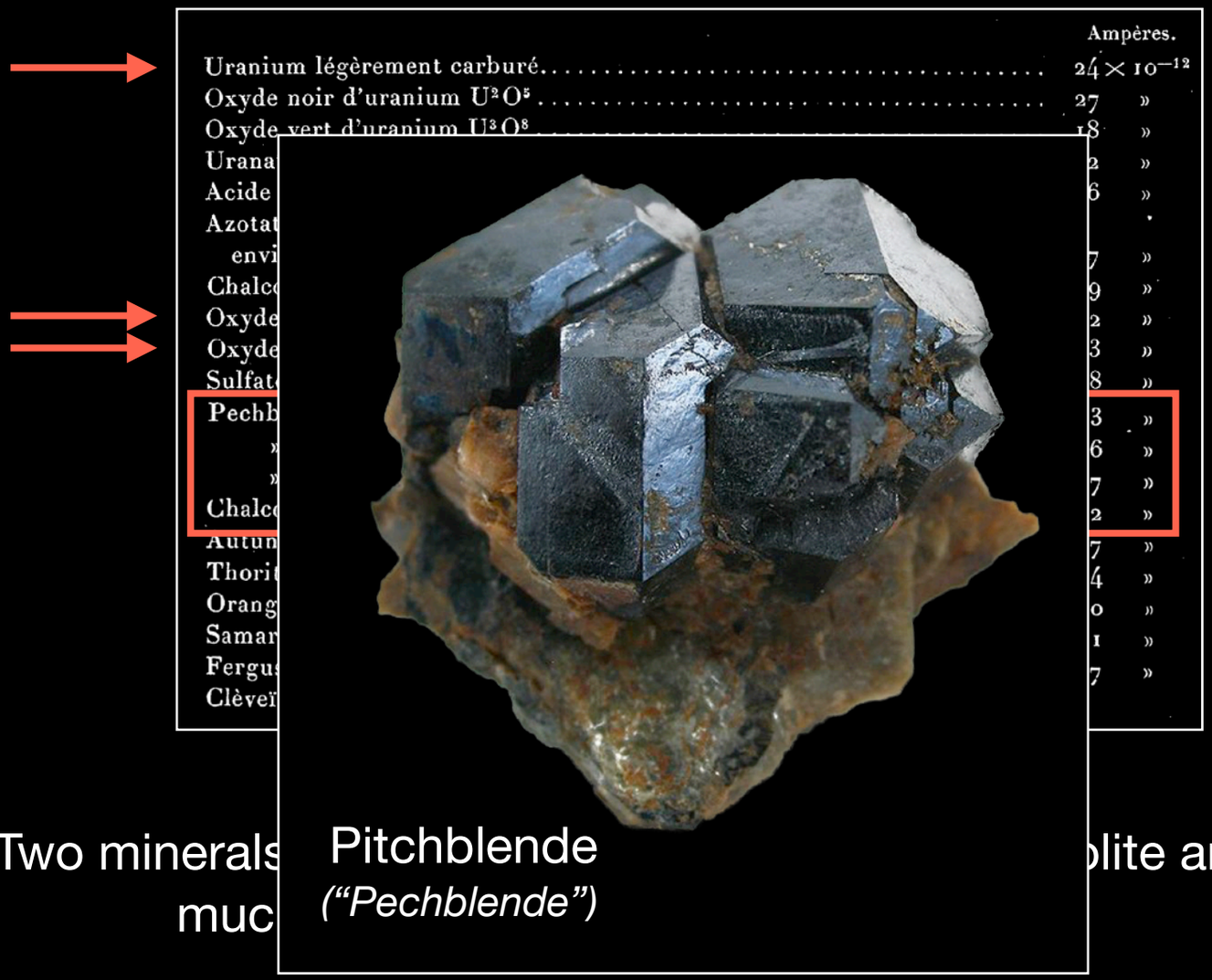
	Ampères.
Uranium légèrement carburé	24×10^{-12}
Oxyde noir d'uranium U^2O^5	27 »
Oxyde vert d'uranium U^3O^8	18 »
Uranates d'ammonium, de potassium, de sodium, environ	12 »
Acide uranique hydraté	6 »
Azotate d'uranyle, sulfate uraneux, sulfate d'uranyle et de potassium, environ	7 »
Chalcolite artificielle (phosphate de cuivre et d'uranyle)	9 »
Oxyde de thorium en couche de 0^{mm}, 25 d'épaisseur	22 »
Oxyde de thorium en couche de 6^{mm} d'épaisseur	53 »
Sulfate de thorium	8 »
Pechblende de Johanngeorgenstadt	83 »
» de Cornwallis	16 »
» de Joachimsthal et de Pzibran	67 »
Chalcolite naturelle	52 »
Autunite	27 »
Thorites diverses	de 2 à 14 »
Orangite	20 »
Samarskite	11 »
Fergusonite, monazite, xénotime, niobite, æschinite	de 3 à 7 »
Clèveïte très active.	

*“I was struck by the fact that the activity of uranium and thorium compounds **appears to be an atomic property** of the element uranium and of the element thorium.”*

“The activity is not destroyed by either physical changes of state or chemical transformations.”

Testing different materials

Uranium and thorium minerals are the most “active”



Pitchblende
(“Pechblende”)

“Two minerals
muc
olite are

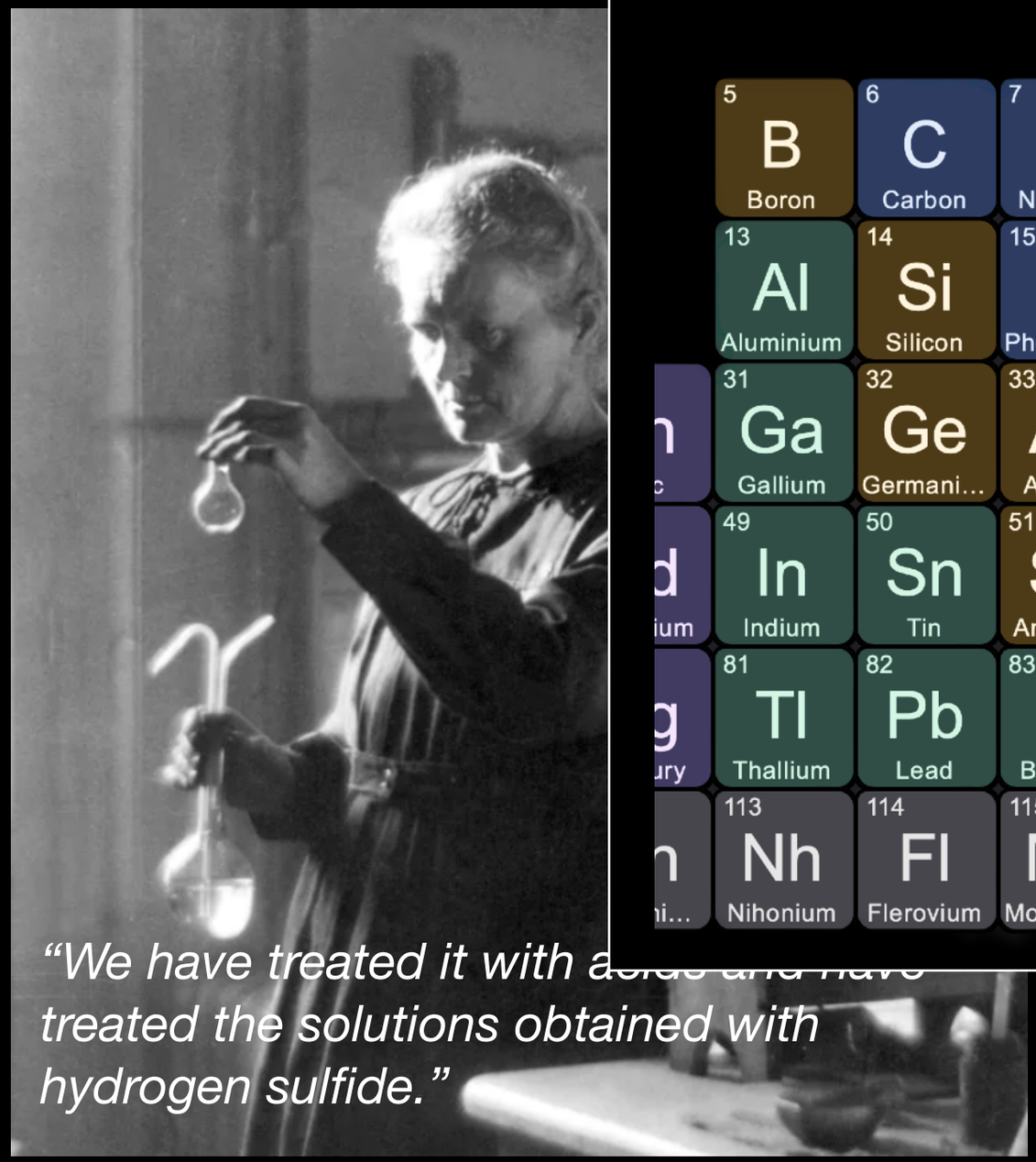
“The fact is very remarkable, and leads to the belief that these minerals may contain an element which is much more active than uranium.”

→ “Radioactive” materials

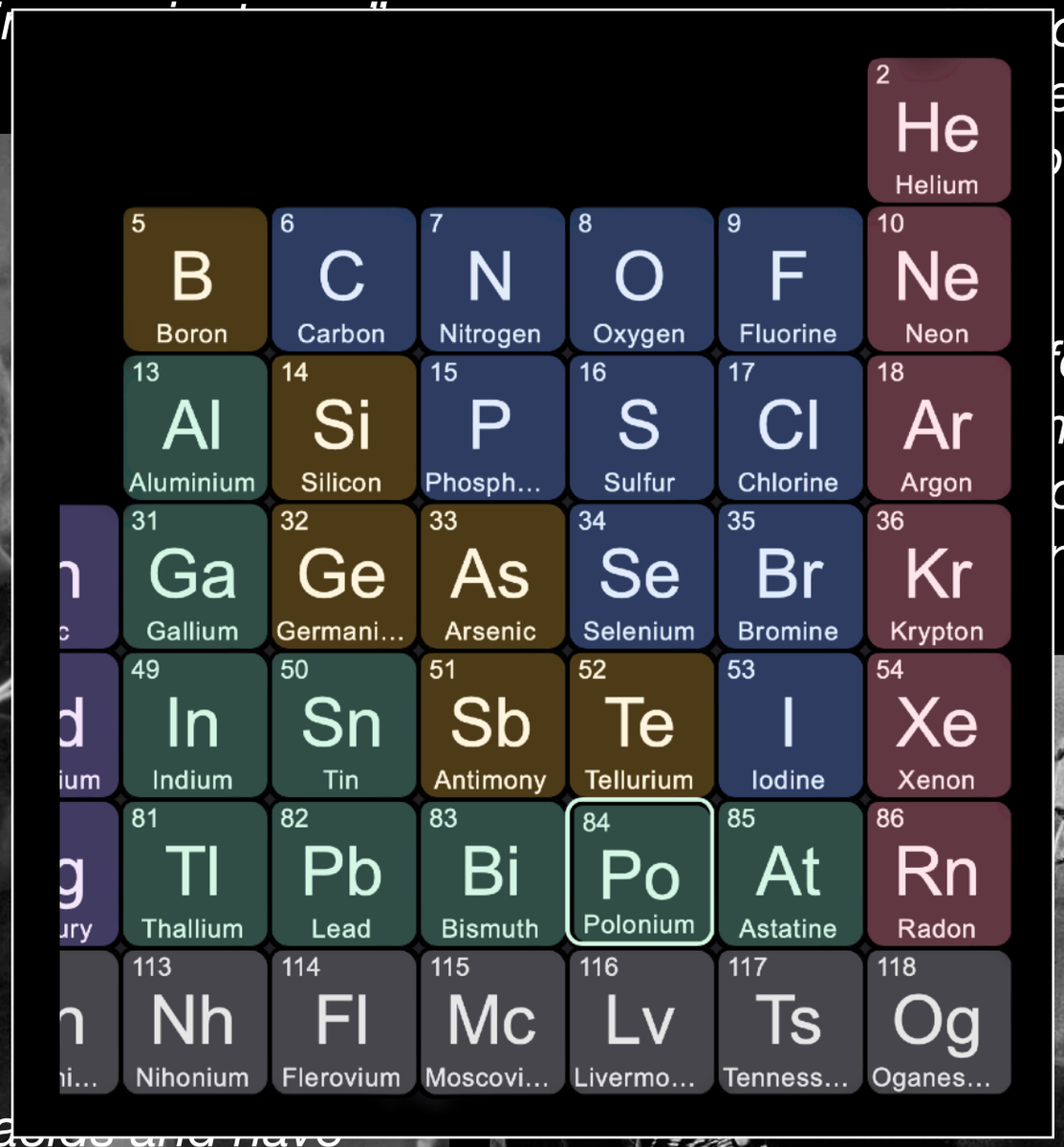
Is there more than uranium?

"We have sought to isolate this substance in pitchblende and experiment has just confirmed the precedi

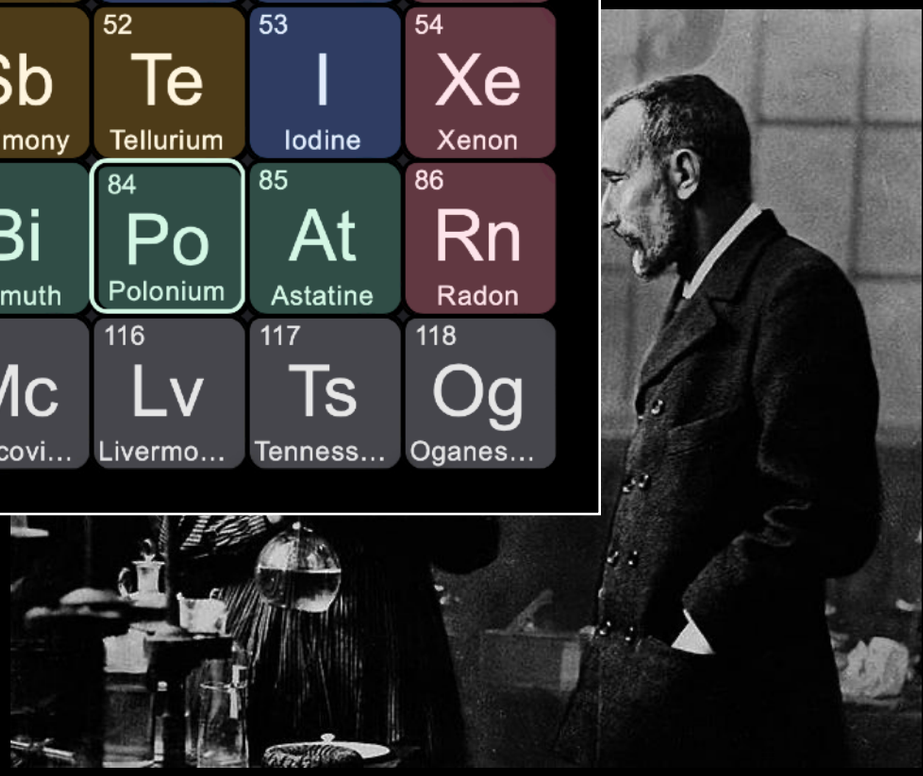
"If the existence of this new metal is confirmed, we
olonium
e country
f us."



"We have treated it with a[illegible] and have treated the solutions obtained with hydrogen sulfide."



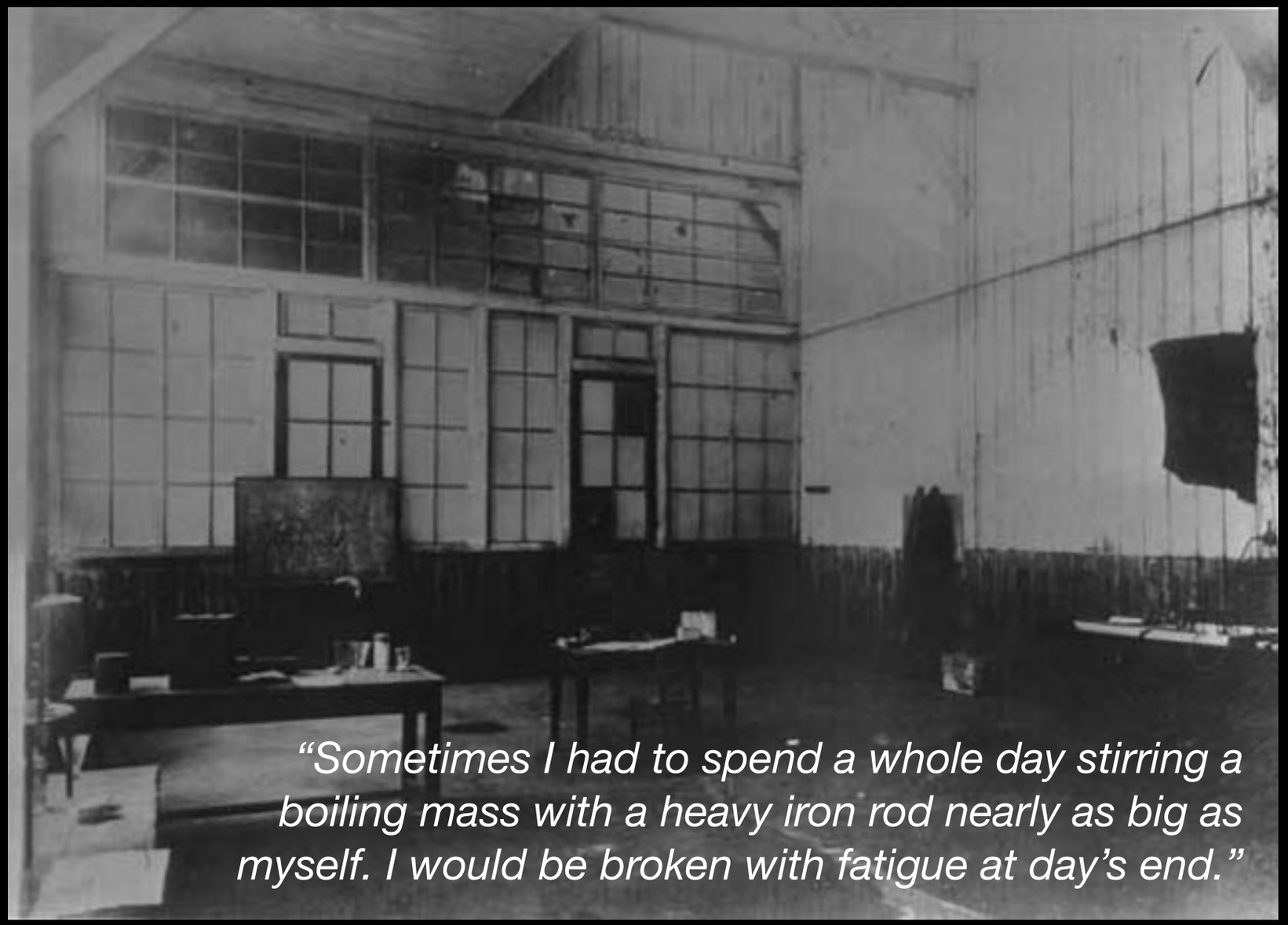
ore that the substance
noved from pitchblende
ot yet reported close to
nalytical properties."



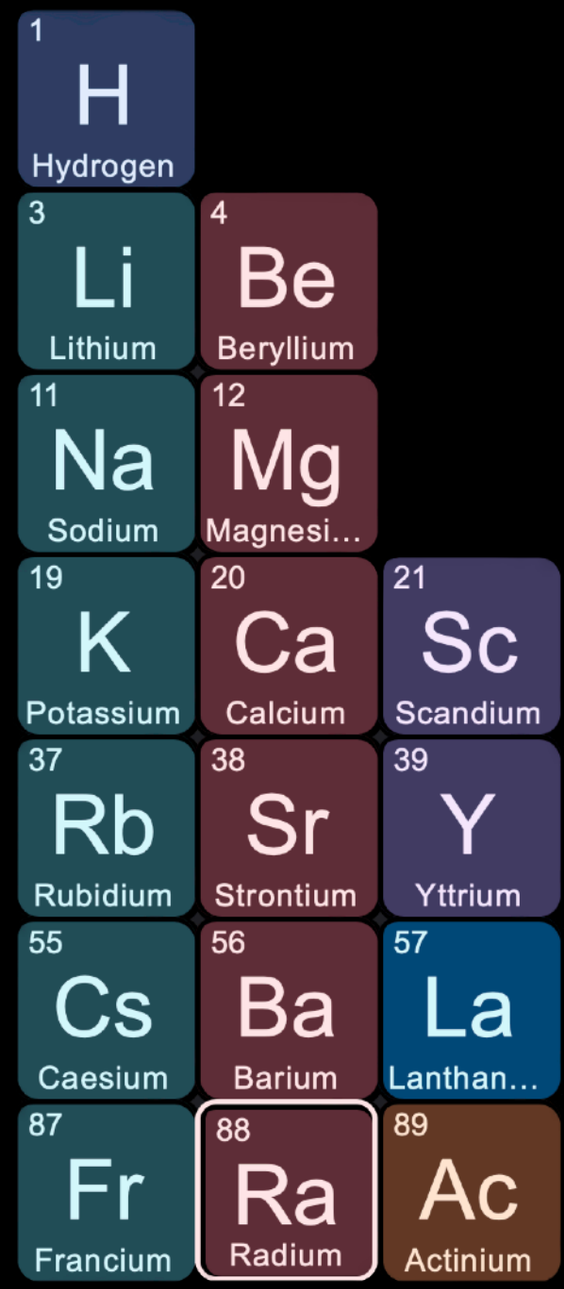
Something else?

“In the course of these researches we have found a second substance strongly radioactive and entirely different in its chemical properties from Polonium.”

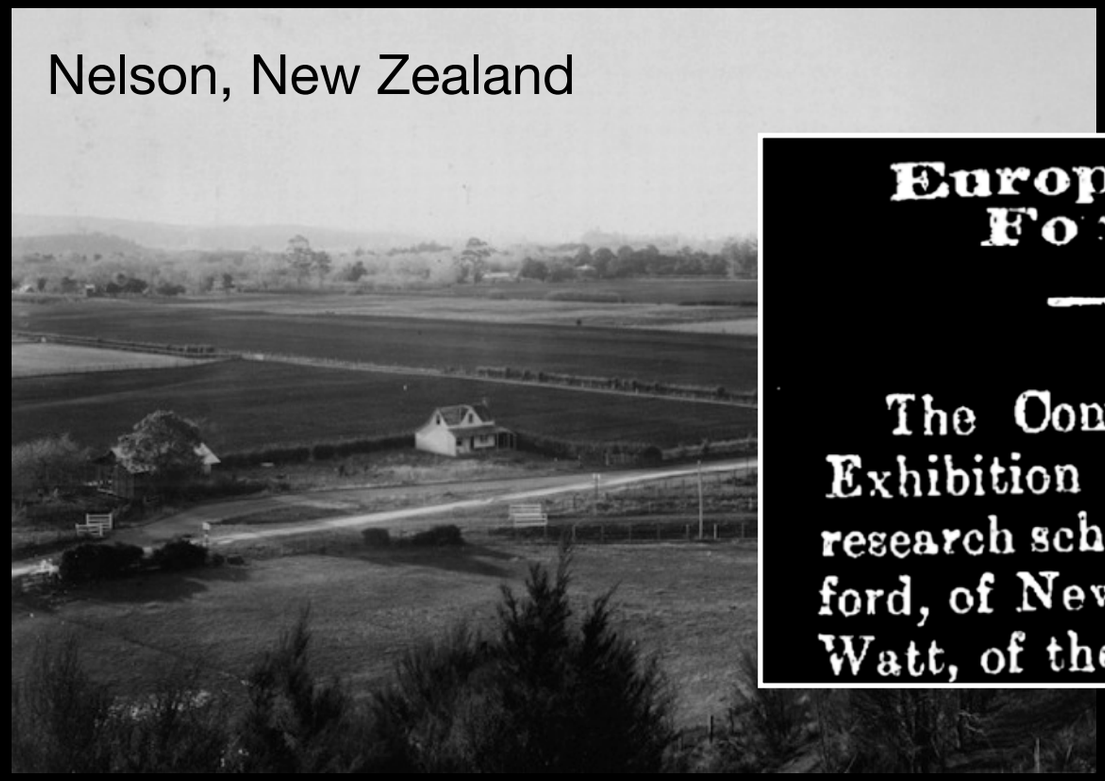
“[We believe] that the new radioactive substance contains a new element to which we propose to give the name radium.”



“Sometimes I had to spend a whole day stirring a boiling mass with a heavy iron rod nearly as big as myself. I would be broken with fatigue at day’s end.”



Ernest Rutherford



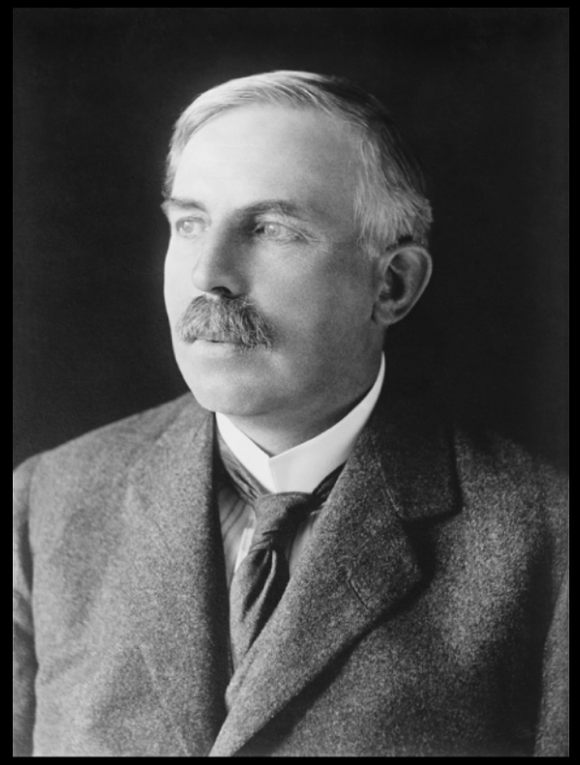
Nelson, New Zealand

His ticket overseas

European and Other Foreign Items

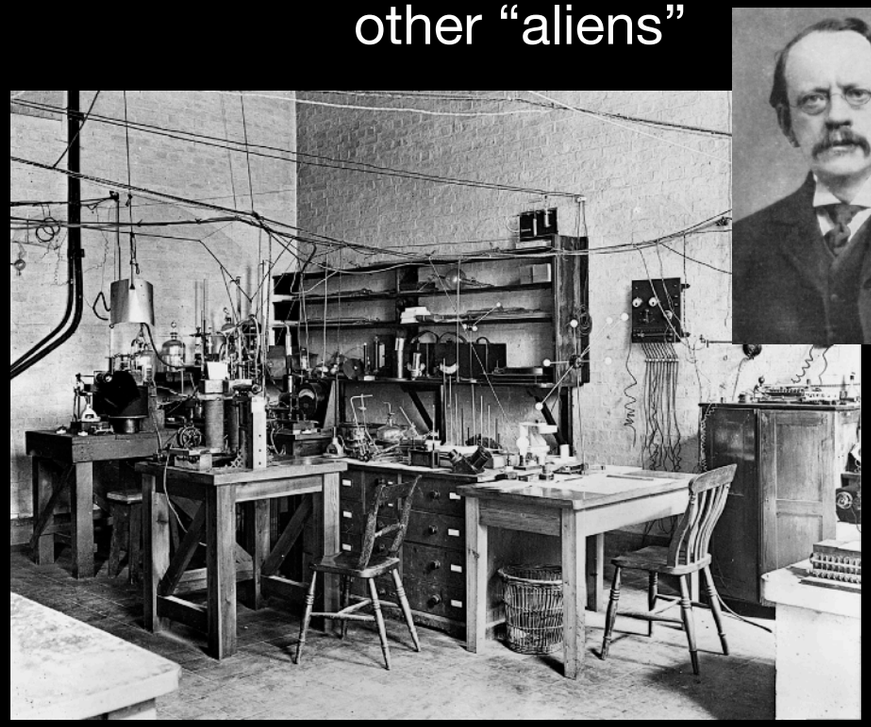
LONDON, July 11

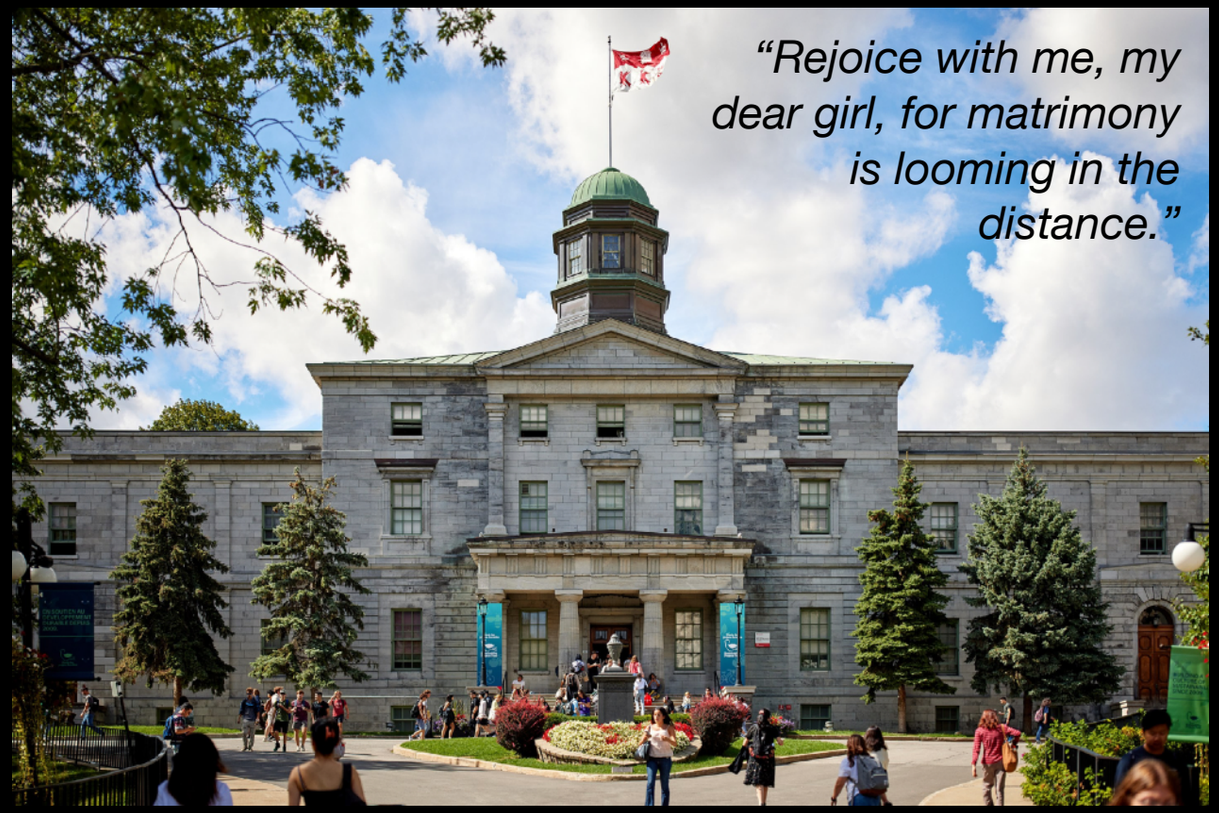
The Commissioners of the 1851 Exhibition have awarded the science research scholarships to Ernest Rutherford, of New Zealand, and Alexander Watt, of the Sydney University.



McGill University, Montreal

At the Cavendish with other “aliens”

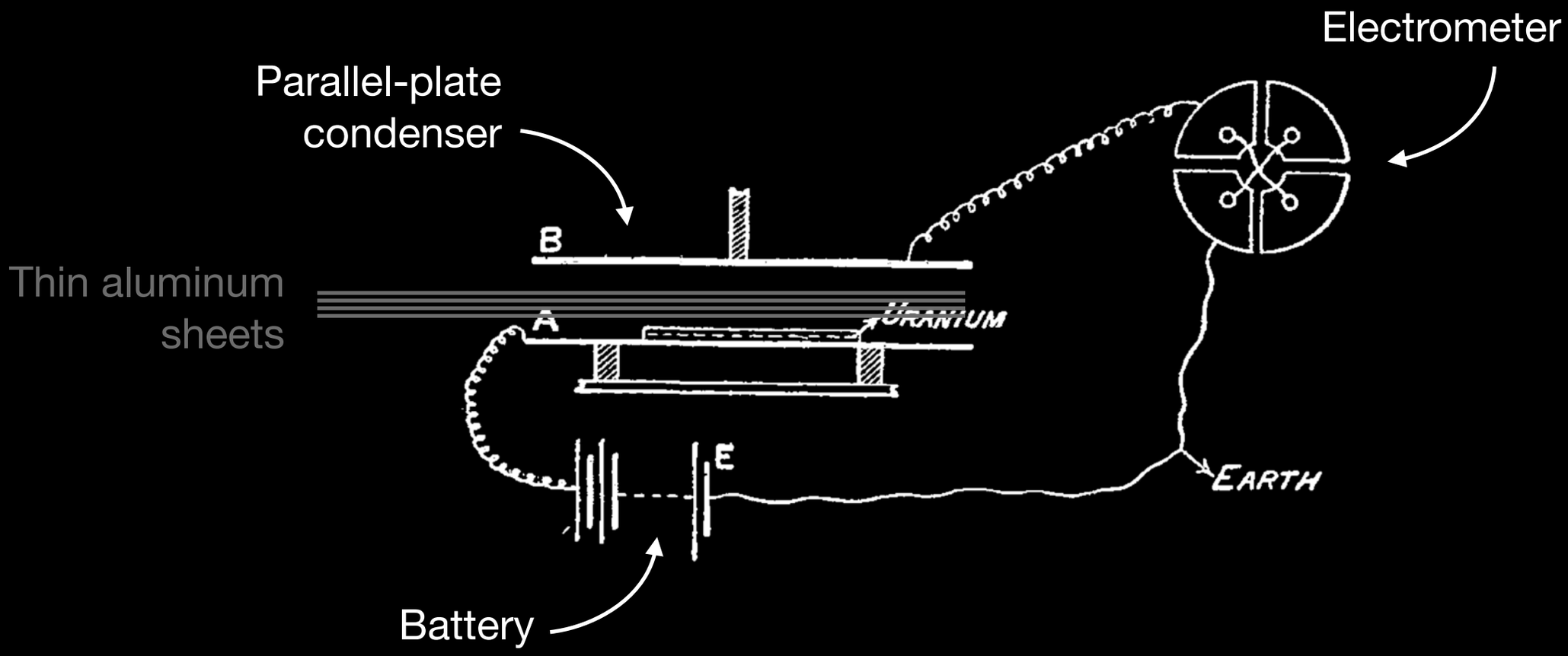




“Rejoice with me, my dear girl, for matrimony is looming in the distance.”

How penetrating are the rays?

Radiation measurement in the “Curie method”:

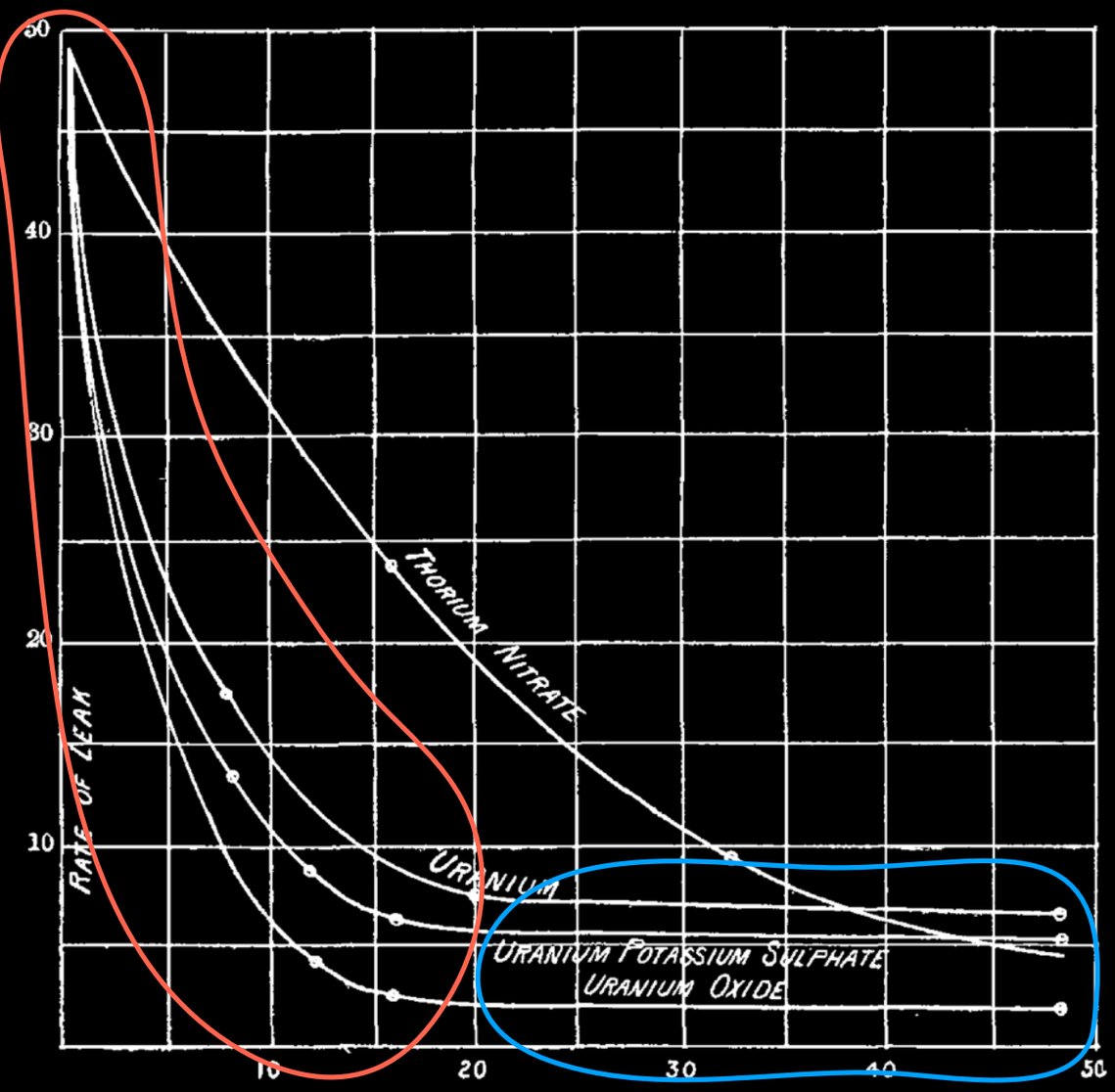


How many sheets are needed to absorb *(“shield”)* the radiation?

Only one kind of rays?

Intensity of radiation

Very fast reduction



Much slower reduction

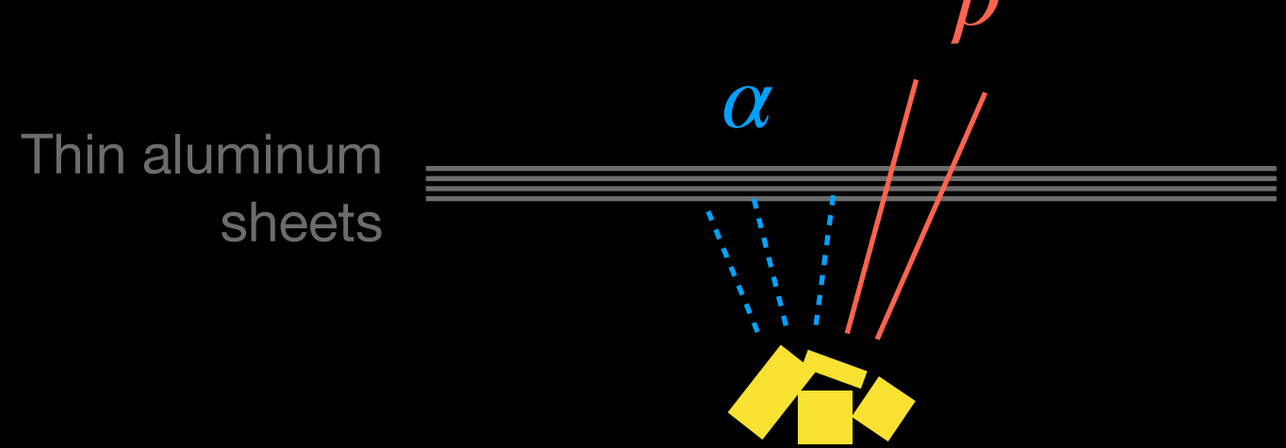
Number of aluminum sheets

“The aluminium foil in this case was about 0.0005 cm thick.”

More than one kind of rays!

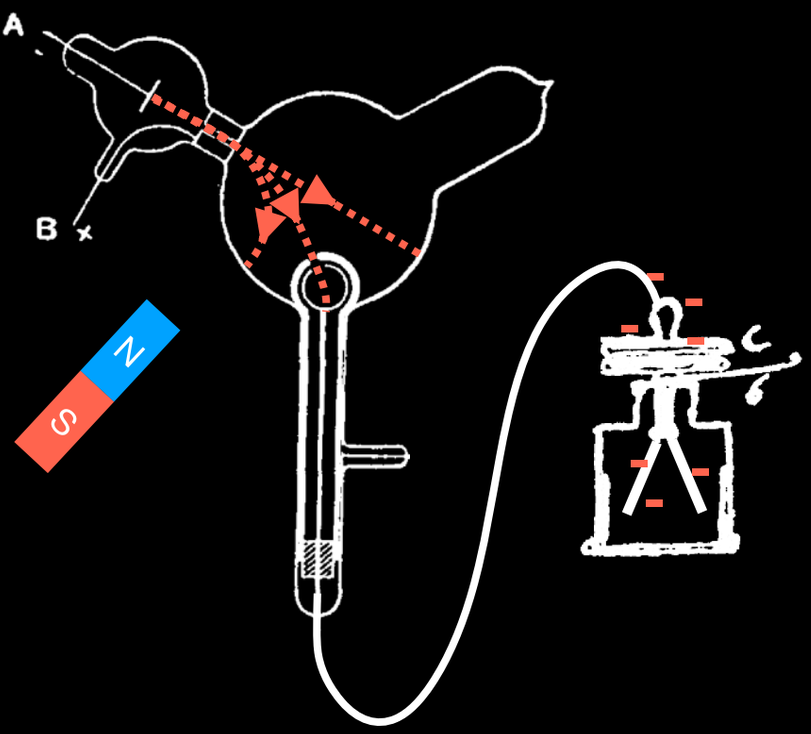
"One that is very readily absorbed, which will be termed for convenience the α radiation …"

"… and the other of a more penetrating character, which will be termed the β radiation.

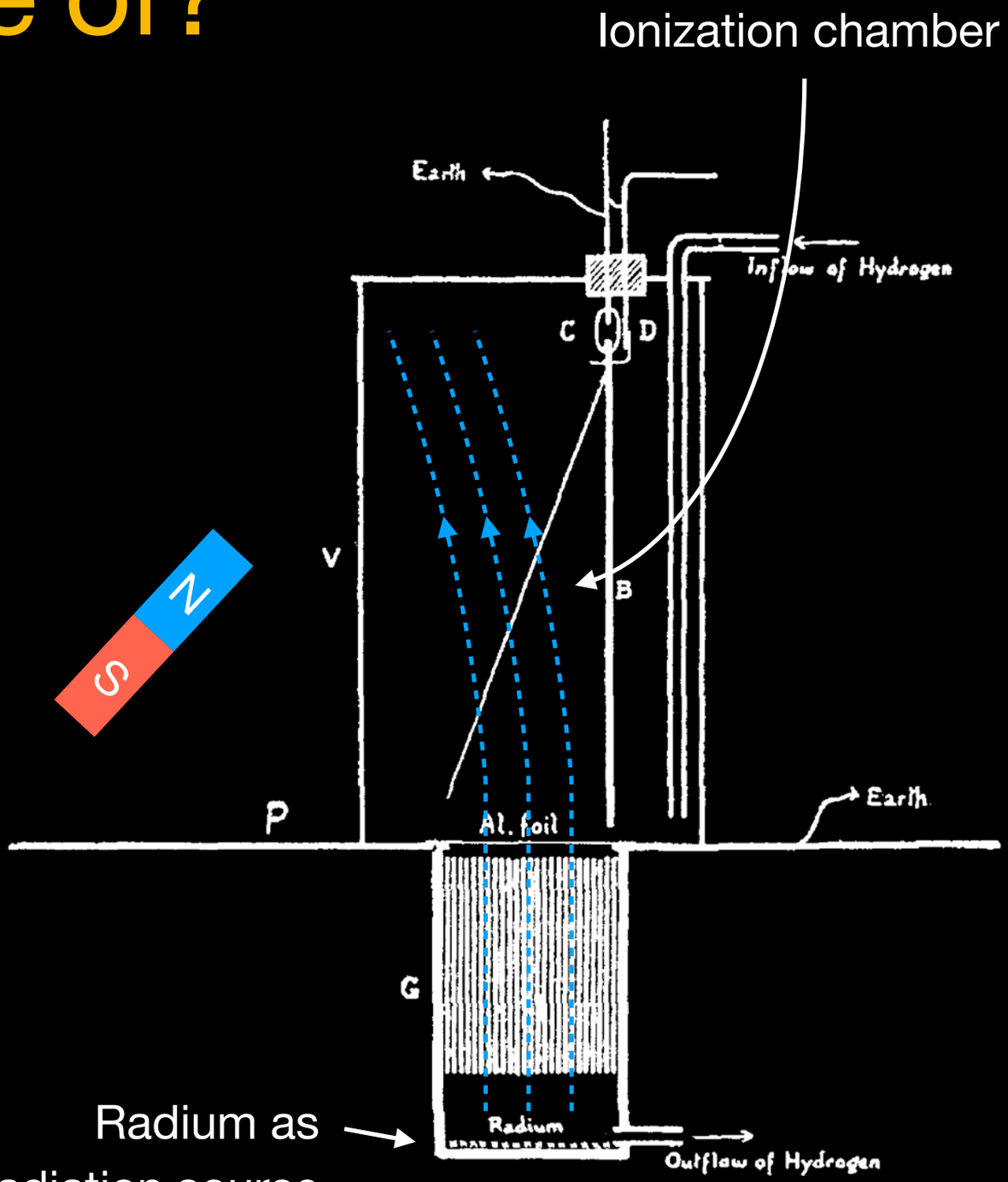


"These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation."

What are α rays made of?



Just like Thomson's experiment

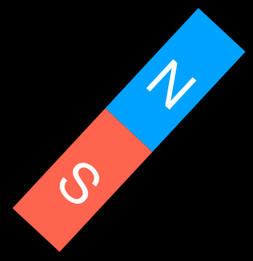


Radium as
α-radiation source

What are α rays made of?

"With the largest electromagnet in the laboratory,
I was only able to deviate about 30 per cent of the α rays."

"I was, however, enabled to make use of the field magnet of a 30 kilowatt Edison dynamo."



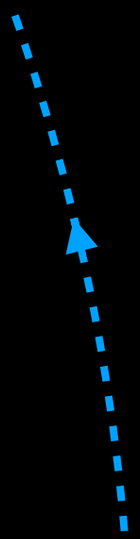
Radium already used as a tool for research!

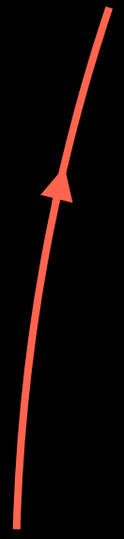
"The sample of radium of greater activity than that normally sold was obtained through the kindness of M. Curie"

"The direction of deviation in a magnetic field was ***opposite in sense to the cathode rays****, i.e. the α* ***rays consisted of positively charged particles."***

Three kinds of radioactivity

α β γ





Paul Villard

Chemist and Physicist in Paris

Positively charged

high e/m

easily stopped

Negatively cl

small $e/$

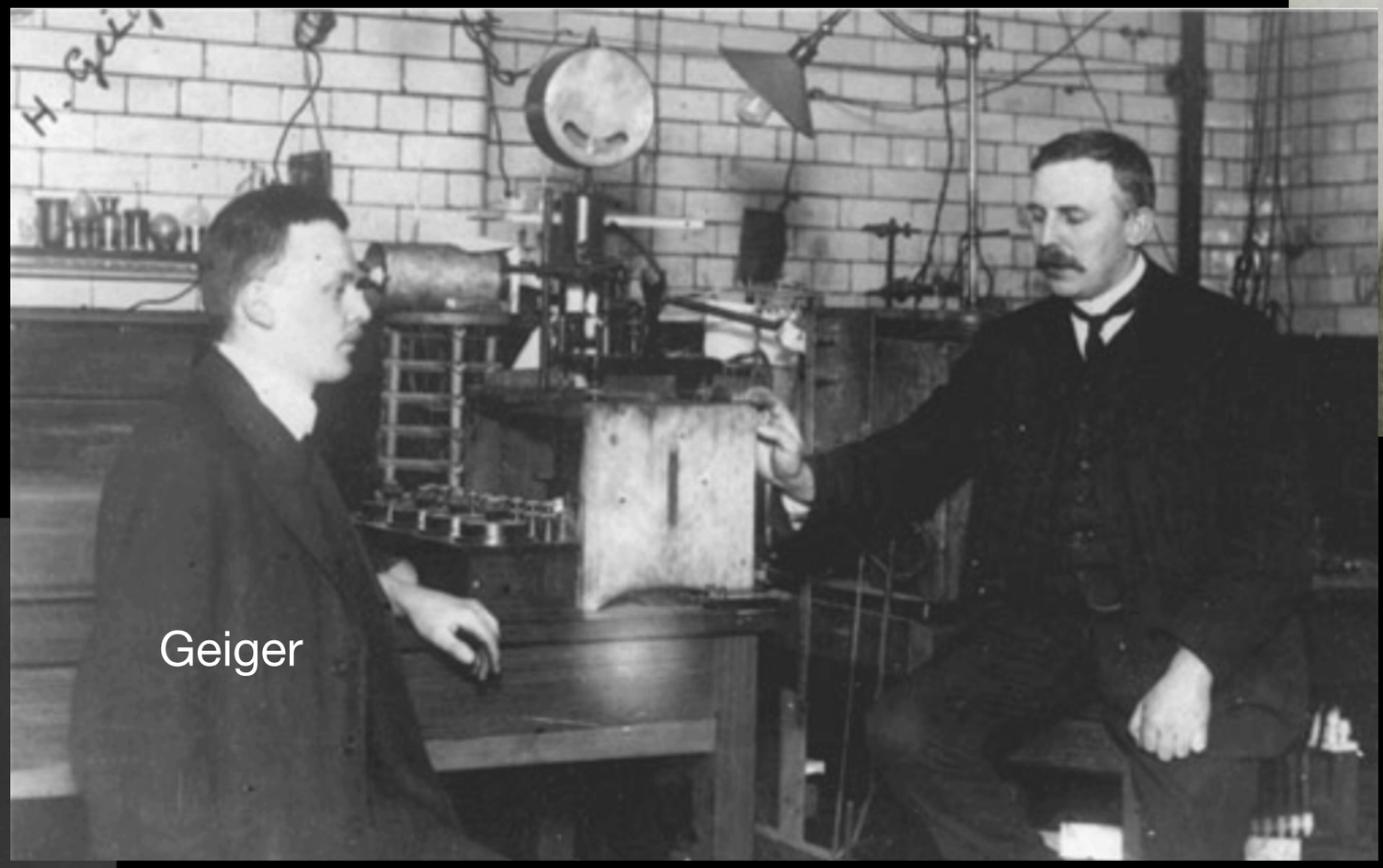
more penetrating

charged

even more penetrating

Moving to Manchester

An offer he could not refuse …



Hans Geiger

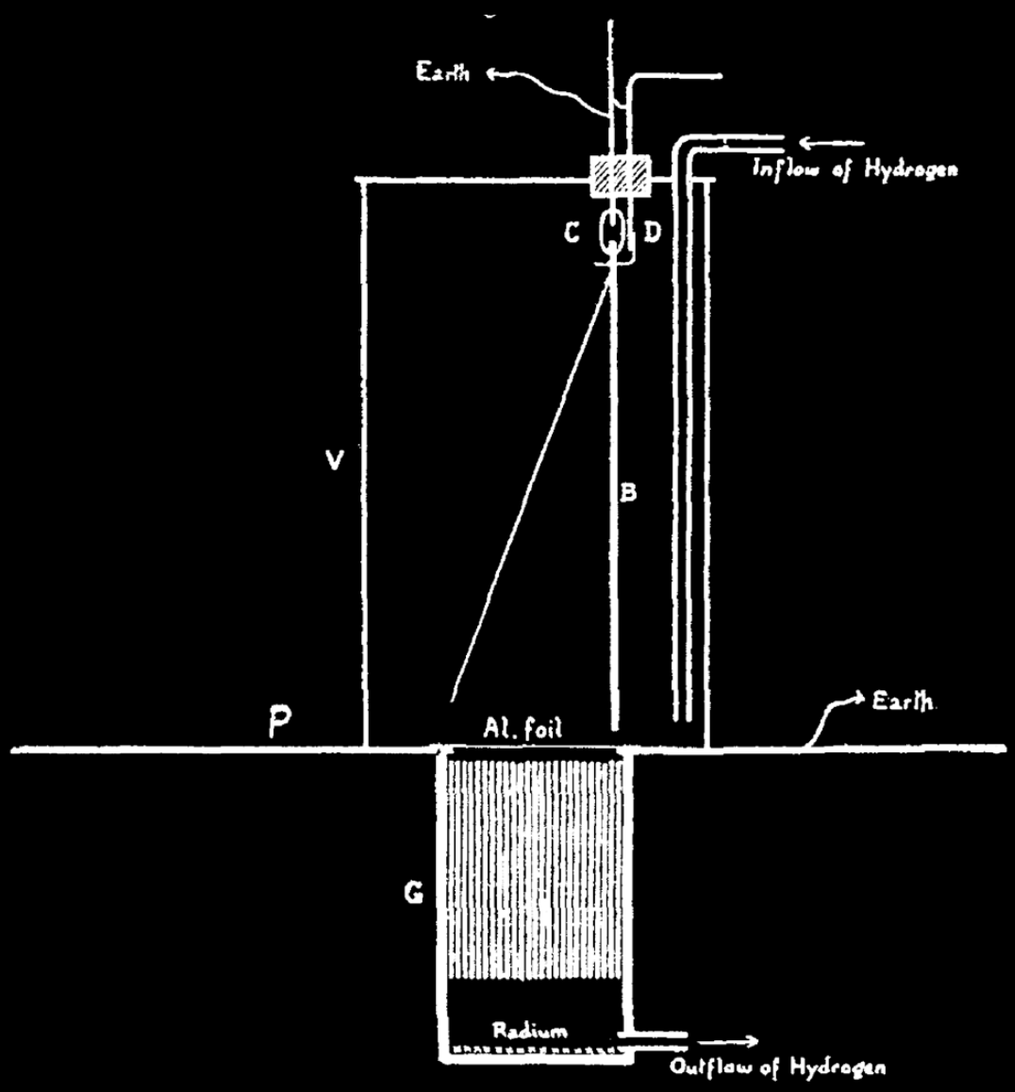
Ernest Marsden

“Everybody seems jolly & anxious to help and I find a most enjoyable absence of convention.”

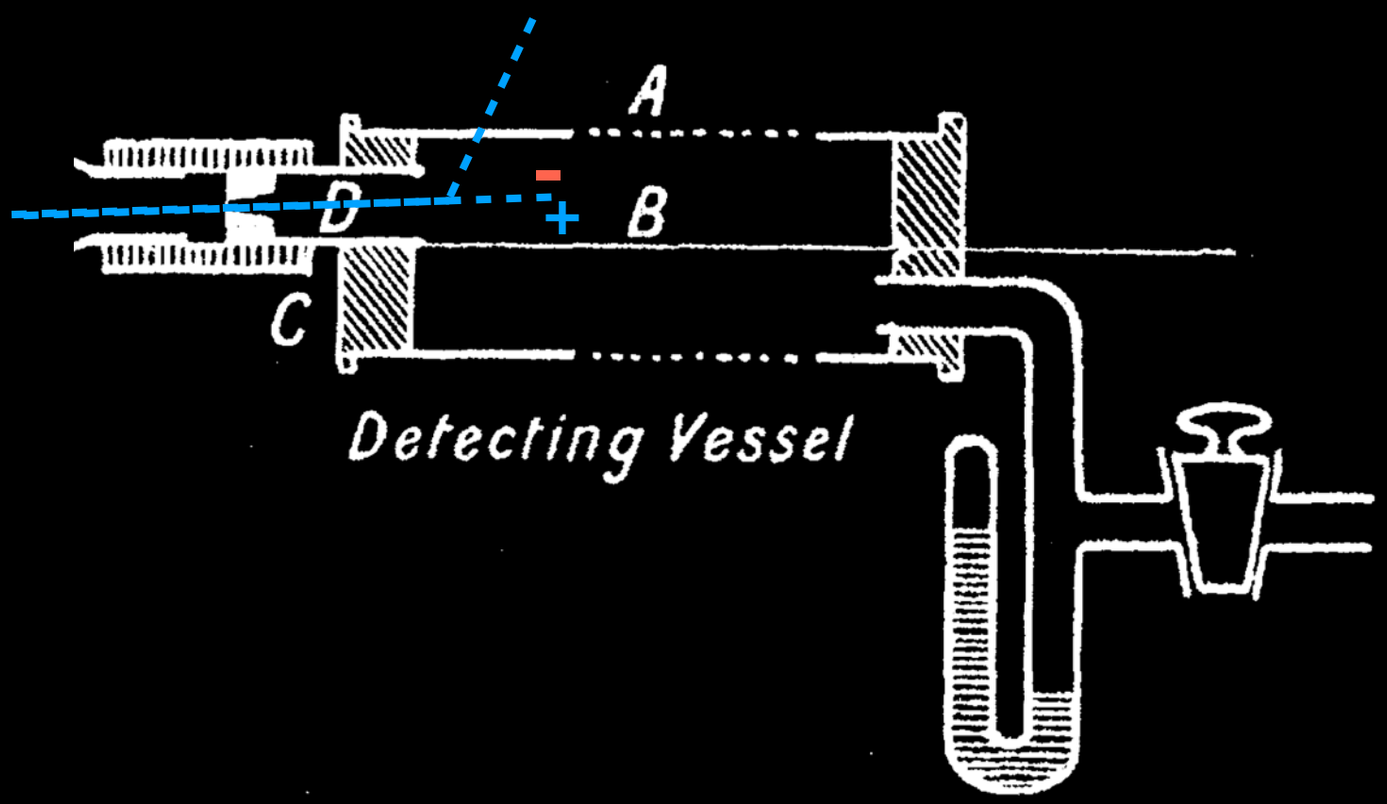
“I find the students here regard a professor as little short of Lord God Almighty. It is quite refreshing after the critical attitude of the Canadian students.”

New instruments

Ionization chamber



The first particle counter
(Rutherford and Geiger)

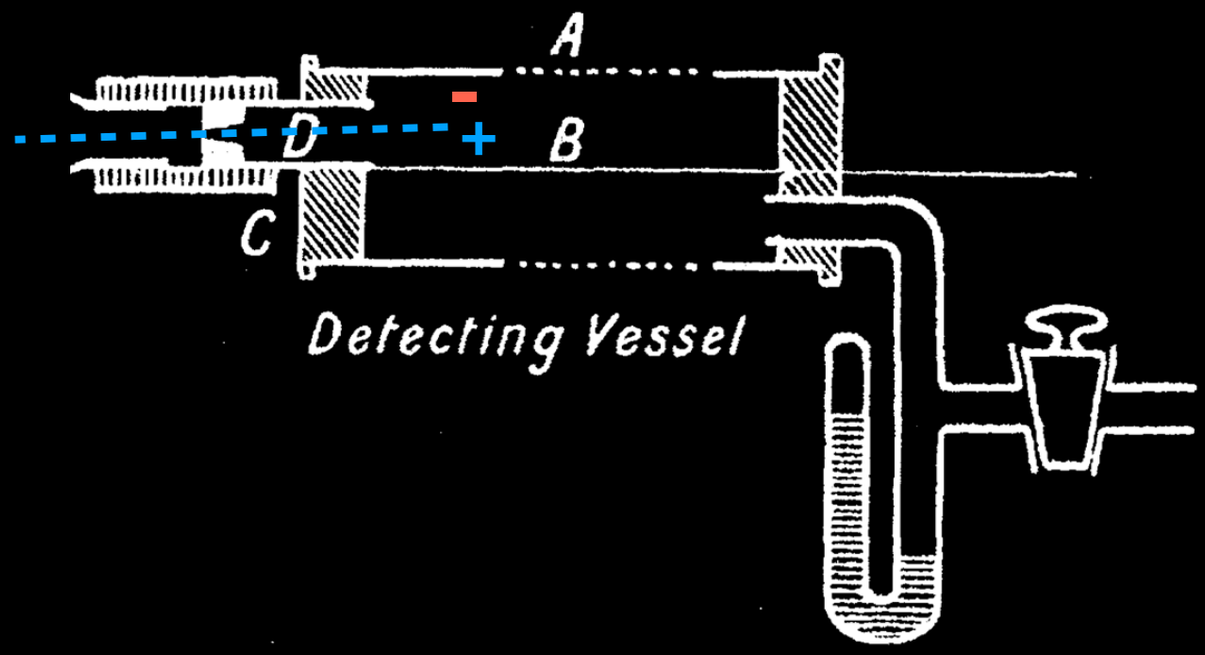


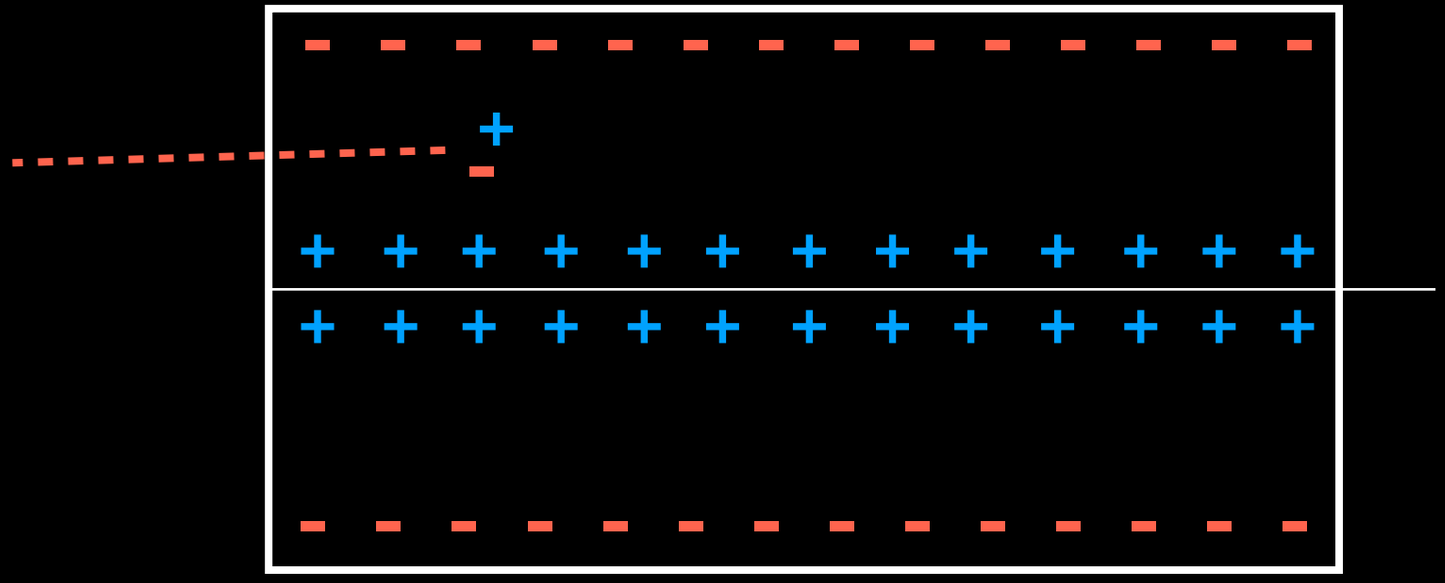
An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

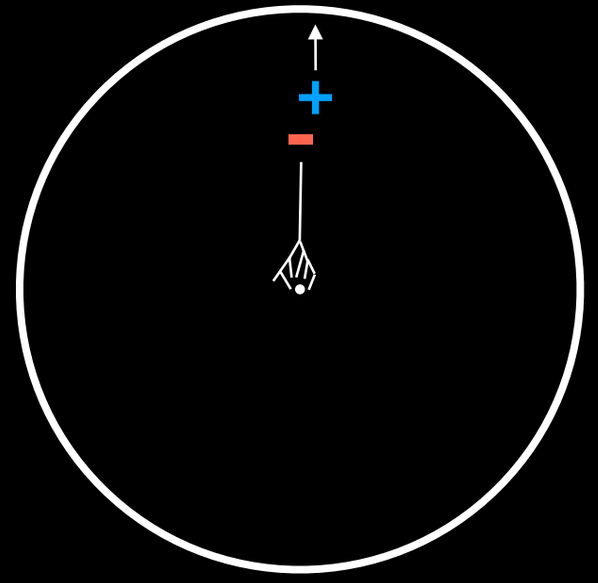
By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D., John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)

Counting particles



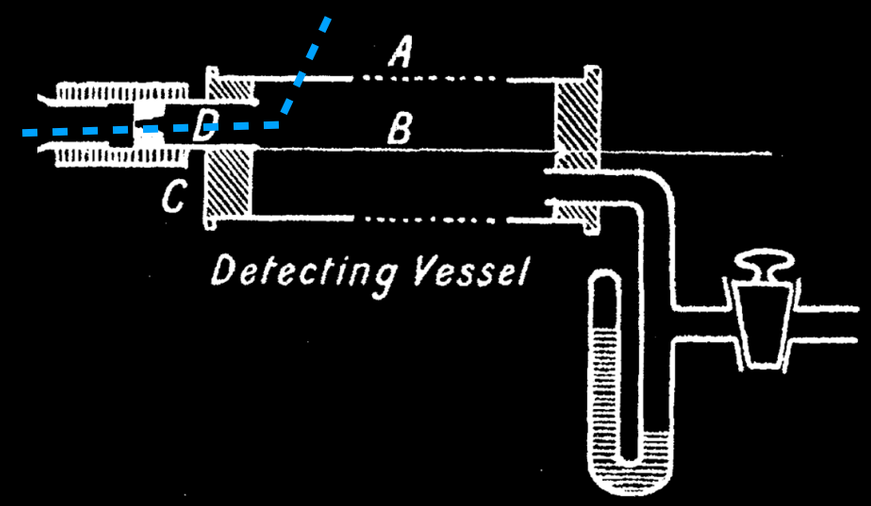


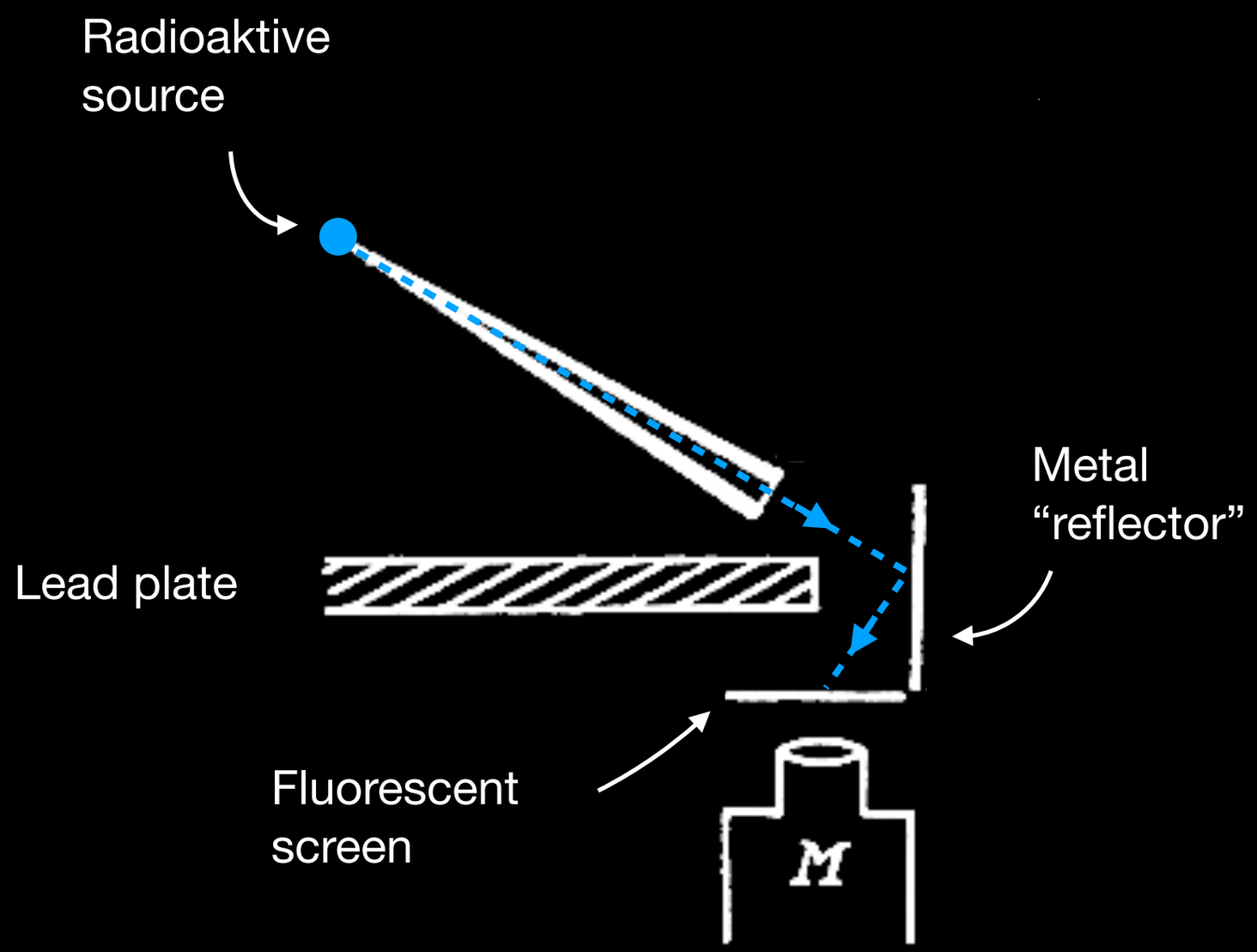


Charge multiplication close to positive wire

Anomalous scattering?

1909

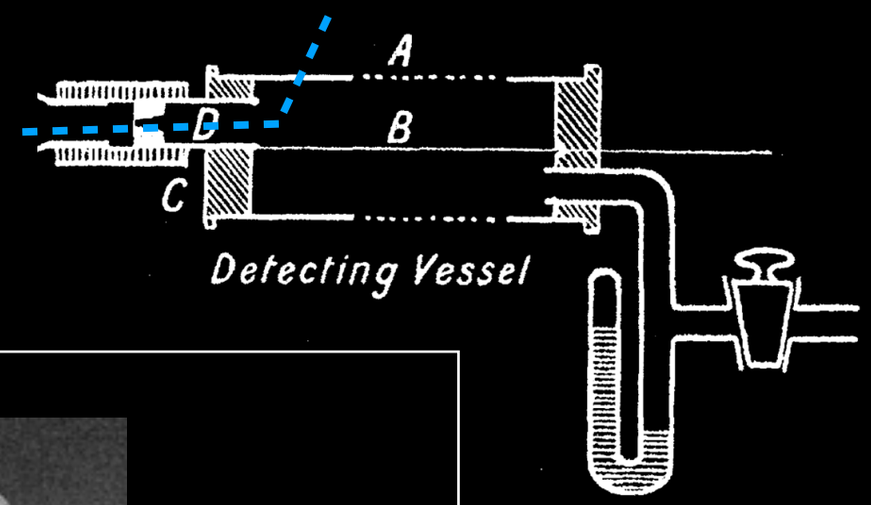


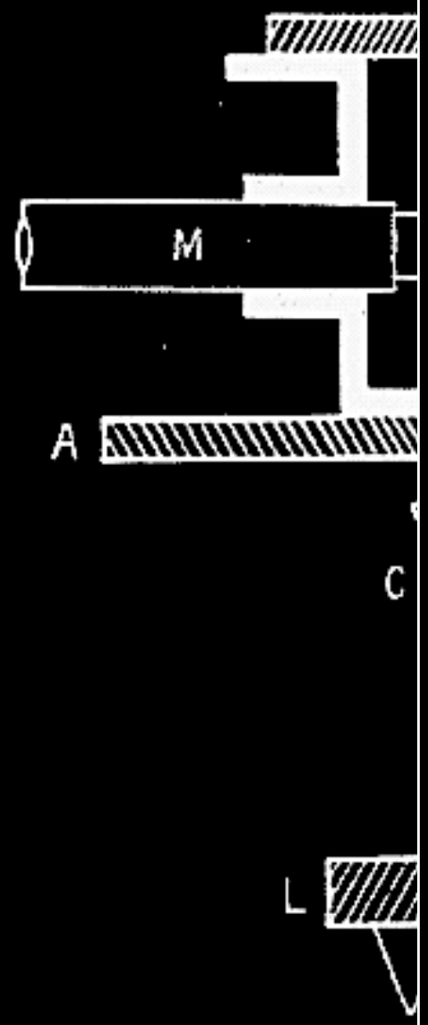


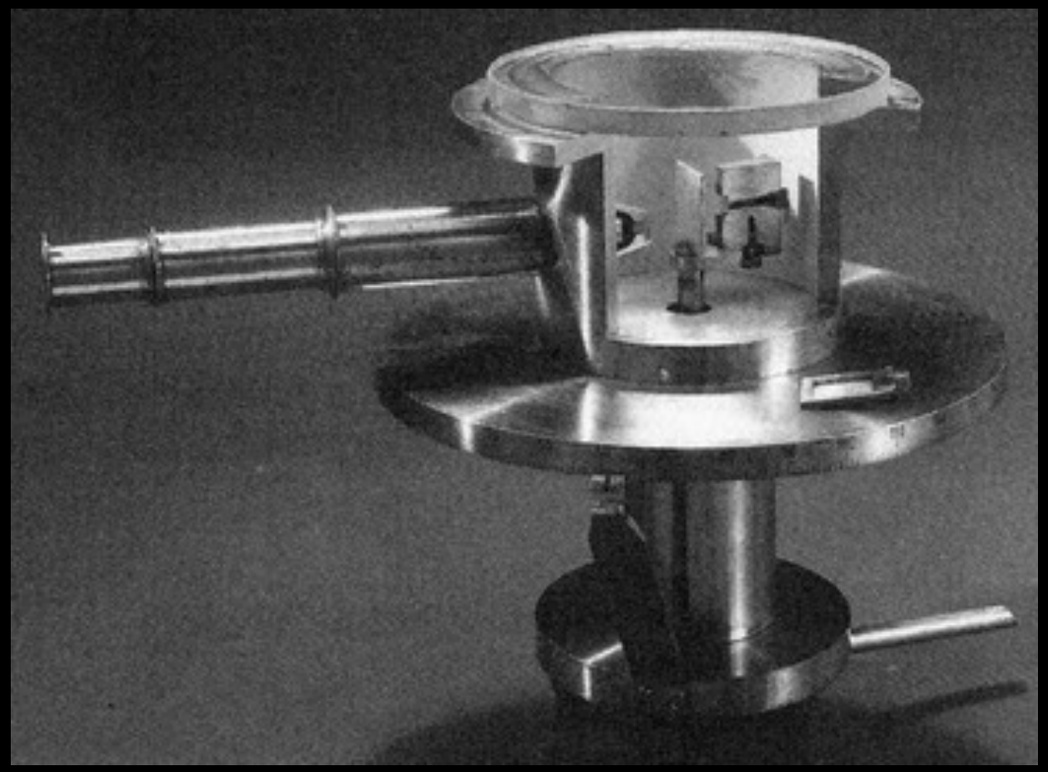
Scattering through wide angle is possible!

Anomalous scattering?

1913







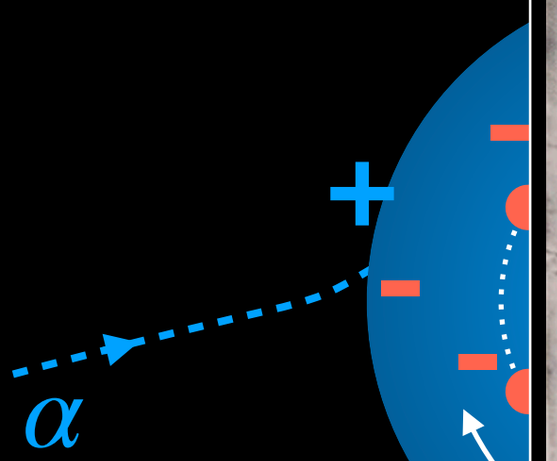
“It was quite the most incredible event that has ever happened to me in my life.”

“It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

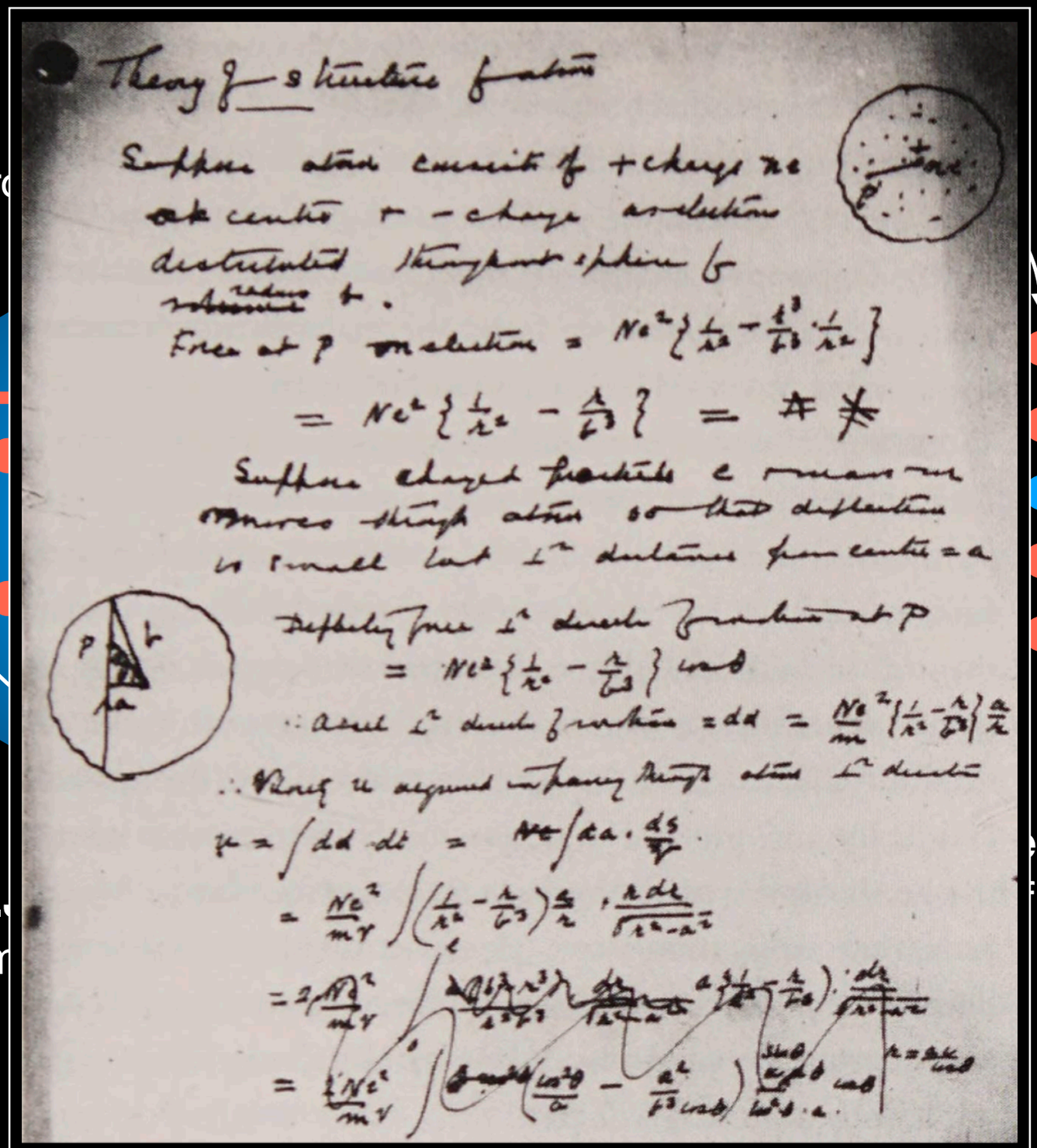
Radioaktive source

The atom has a nucleus!

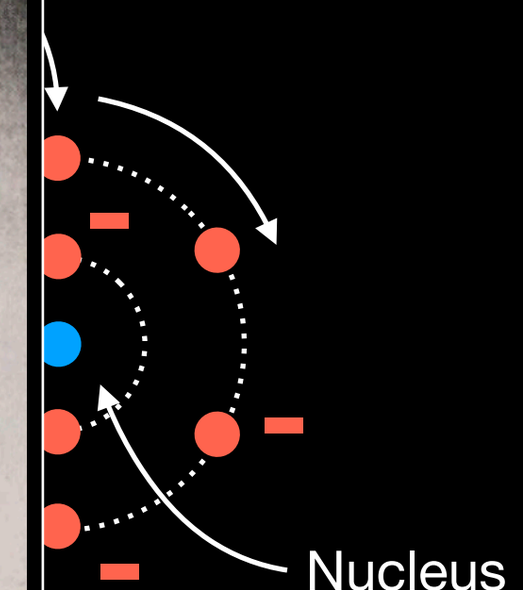
Electro



J.
"Plum



Rutherford's calculations describing the scattering



rford's
the atom

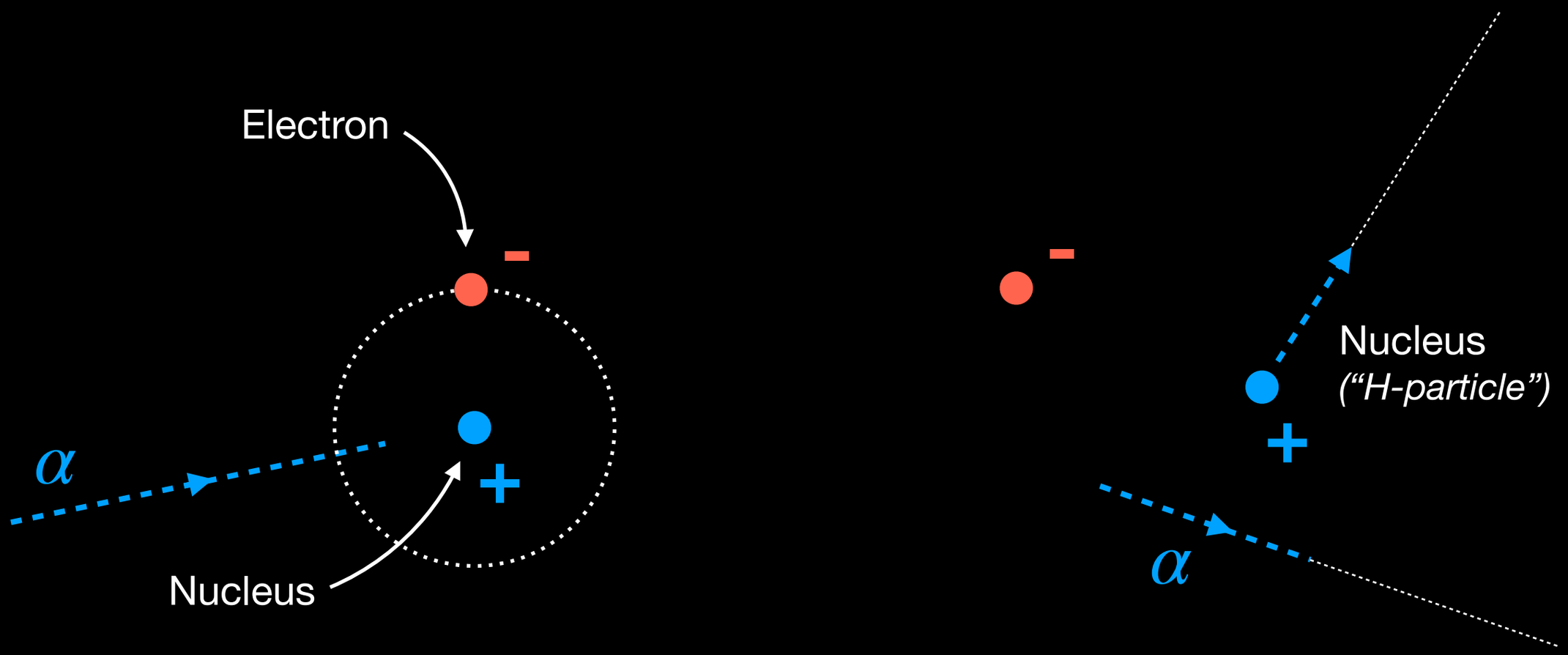
WW1 interrupts science

Marie Curie:
invests Nobel prize money in war bonds,
organizes a mobile X-ray service along the front

Rutherford and Thomson:
Serve on the Admiralty physics board

What is the nucleus made of?

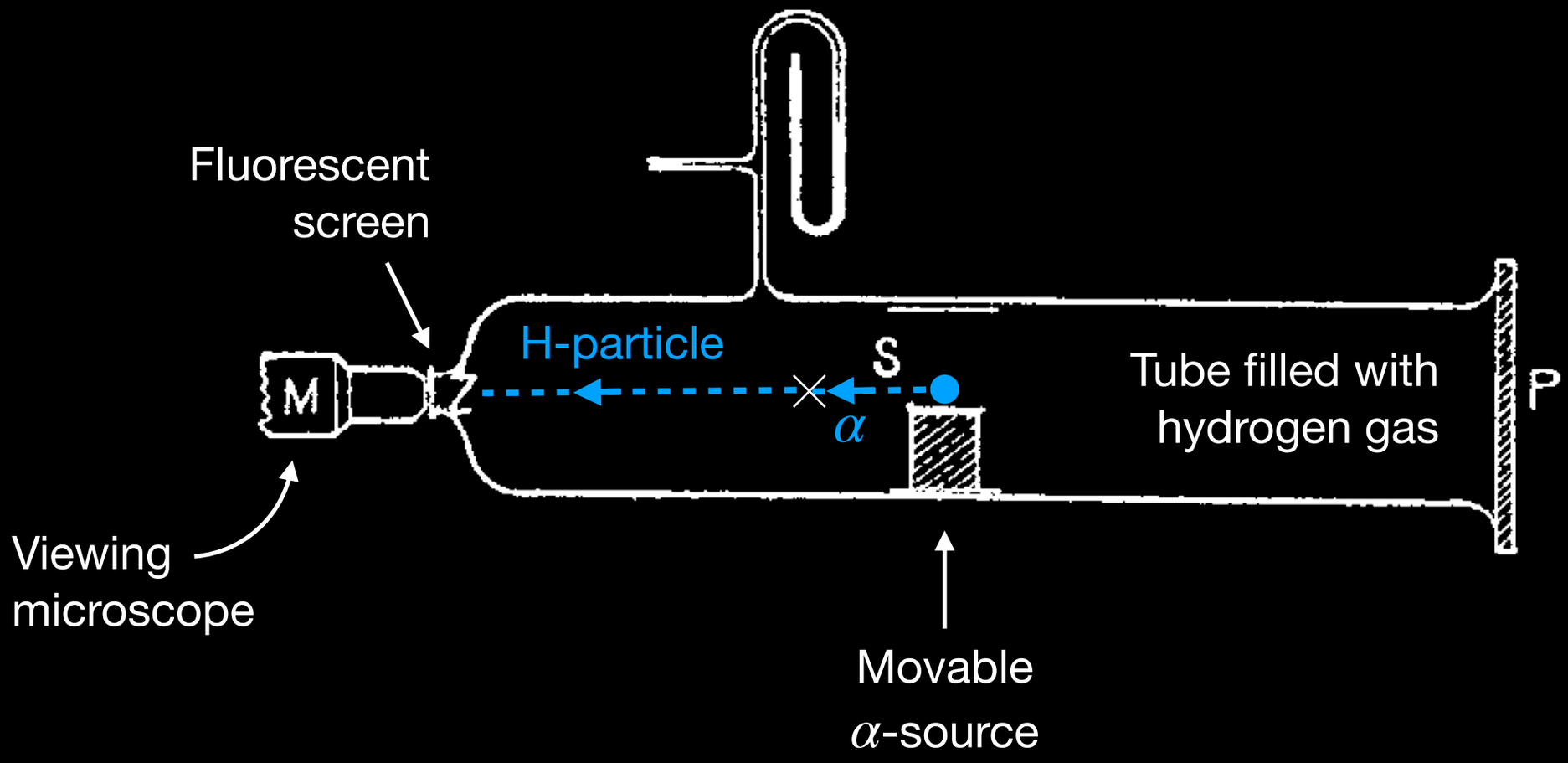
Rutherford: "α particles can collide with the nucleus of a hydrogen atom"



"In an end-on collision, the H-particle will have about four times the range of the α-particle producing it."

What is the nucleus made of?

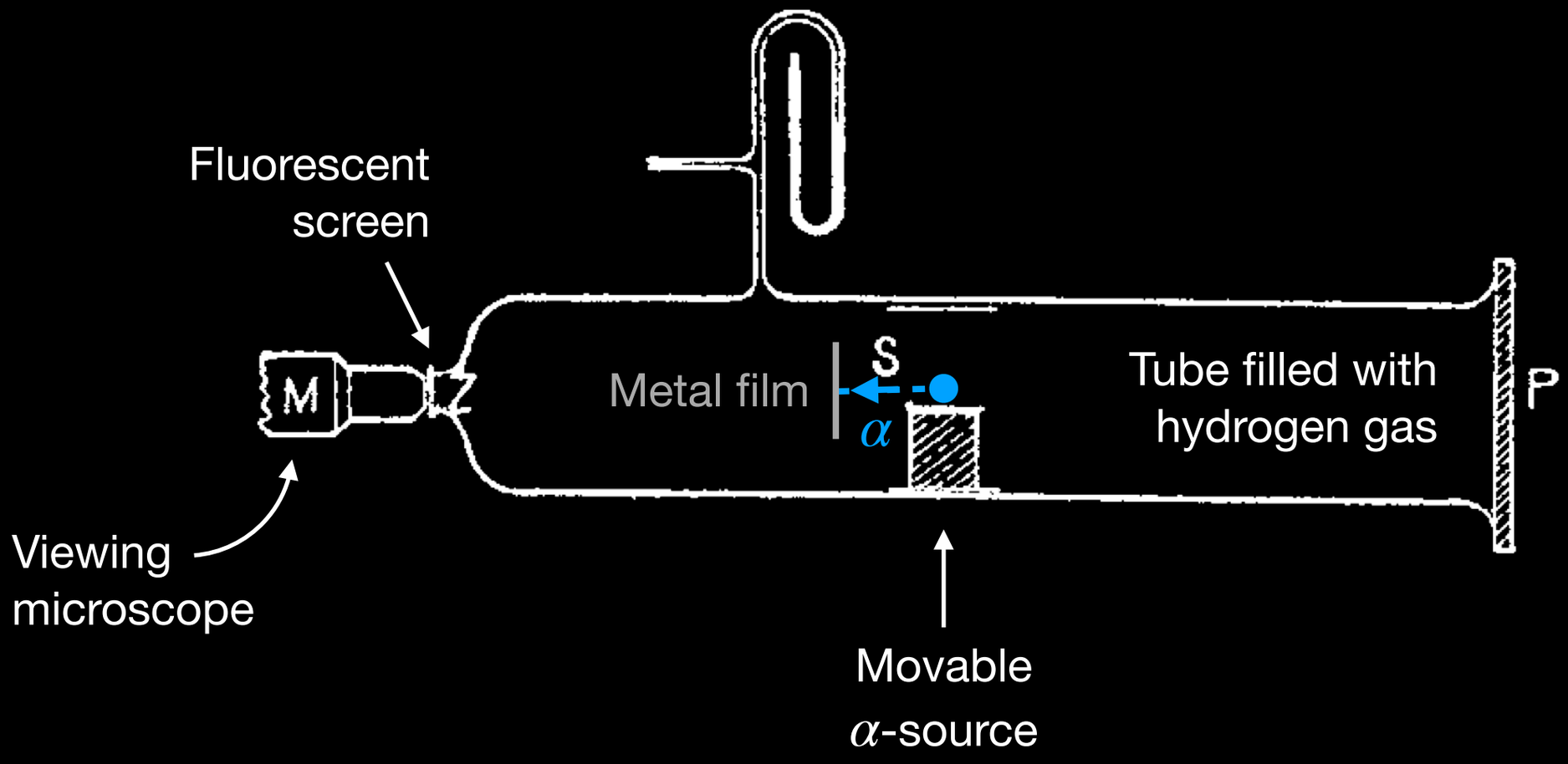
Marsden takes the first step



Are the H-particles produced from the hydrogen gas, or another radiation component coming from the α-source?

What is the nucleus made of?

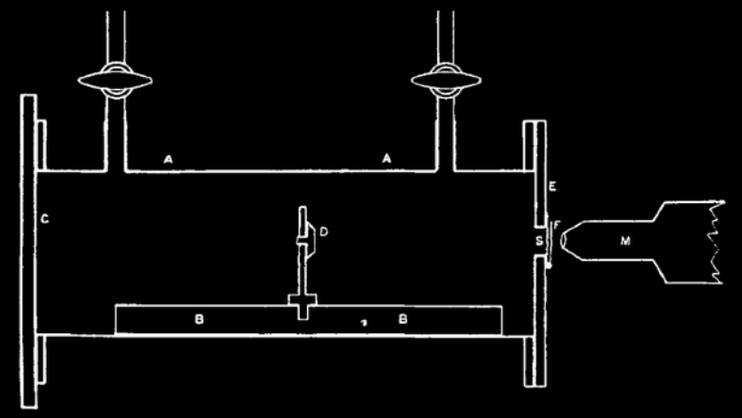
Marsden takes the first step

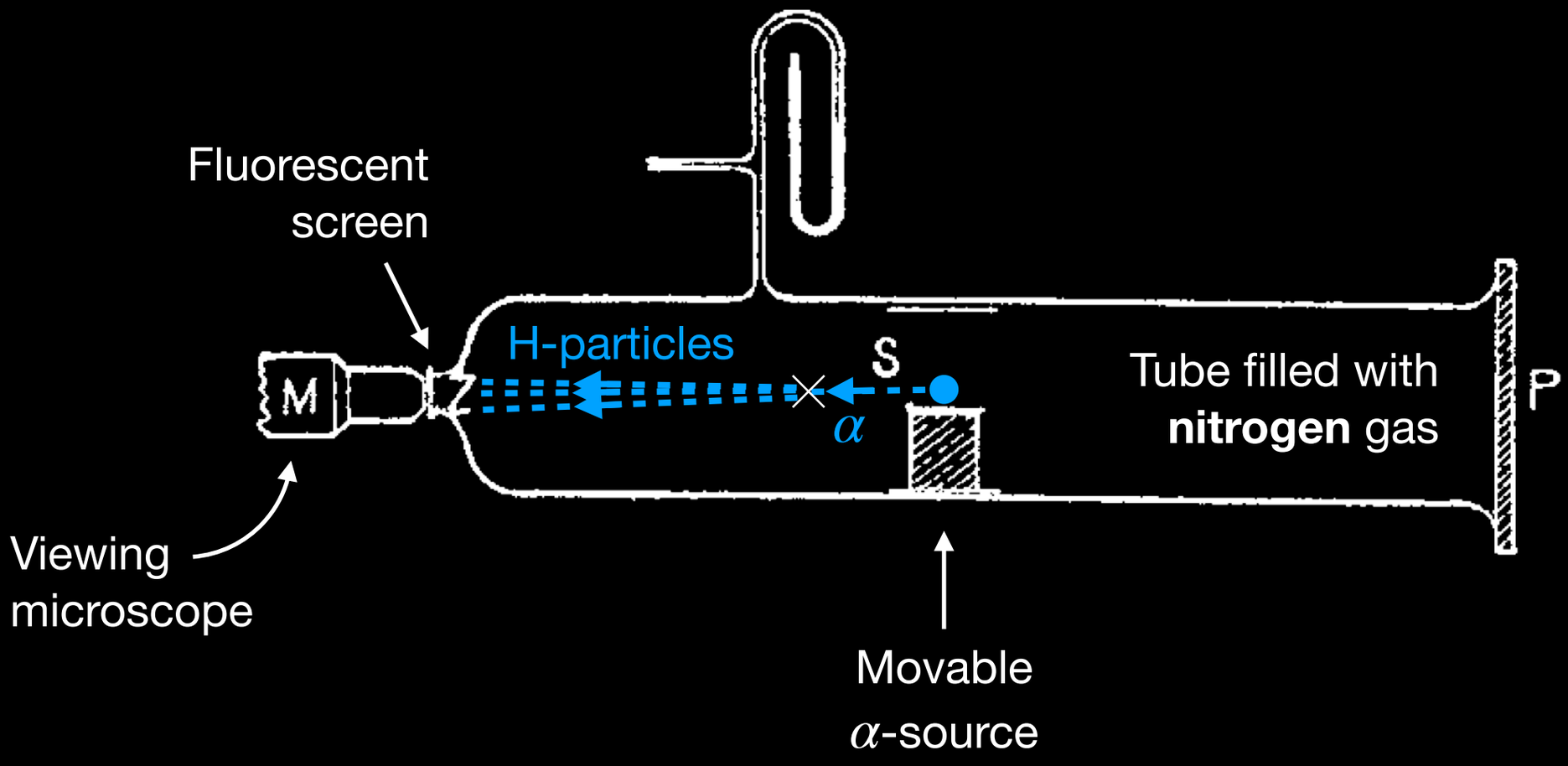


Metal film absorbs α-particles <u>before</u> they can produce H-particles

What is the nucleus made of?

Rutherford continues



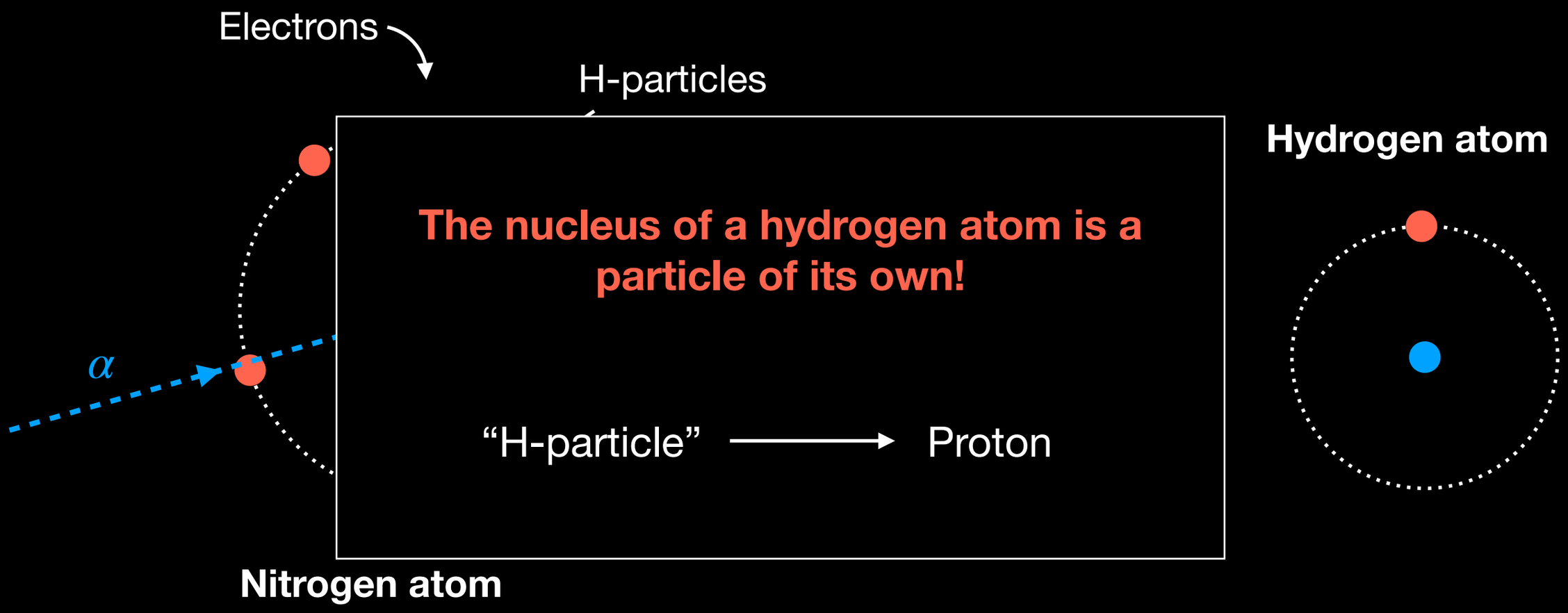


"A surprising effect was noticed, however, when dried air was introduced. The number of scintillations was increased and was about twice that observed when the air was exhausted."

Rutherford's interpretation

April 1919

"Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration."



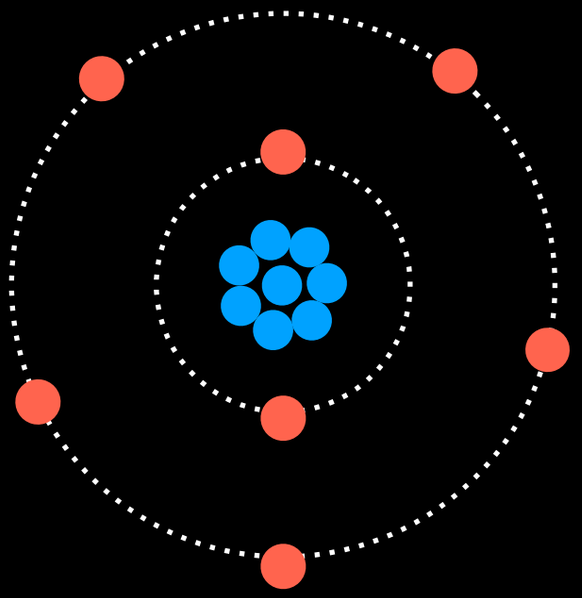
"We must conclude that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus."

“Nuclear chemistry”

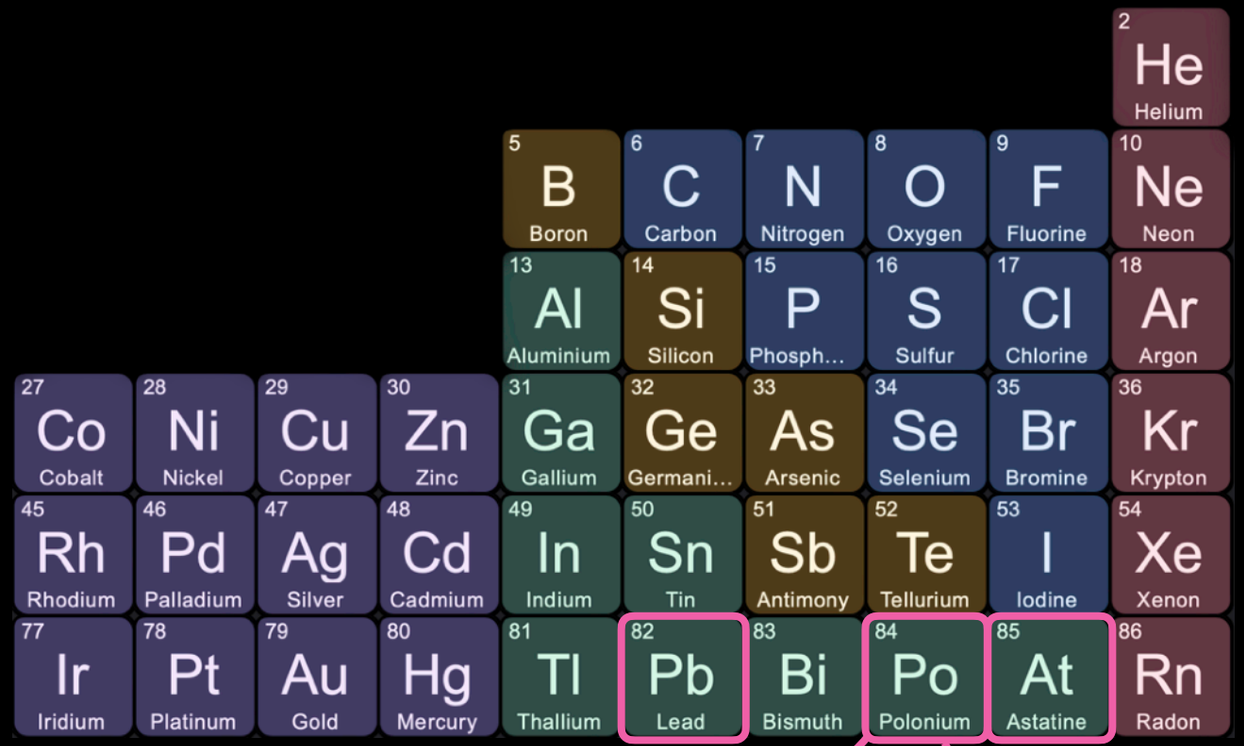
Proton

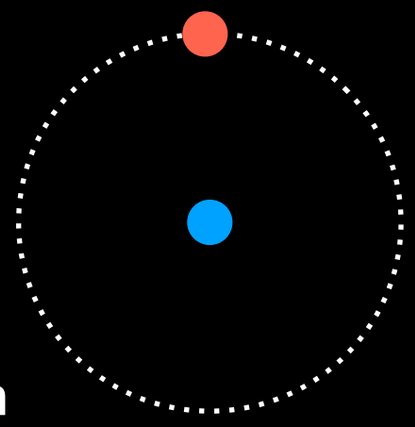
Electron

Atoms are not “elementary”, they have their own building blocks!



Nitrogen
(Heavier than hydrogen)



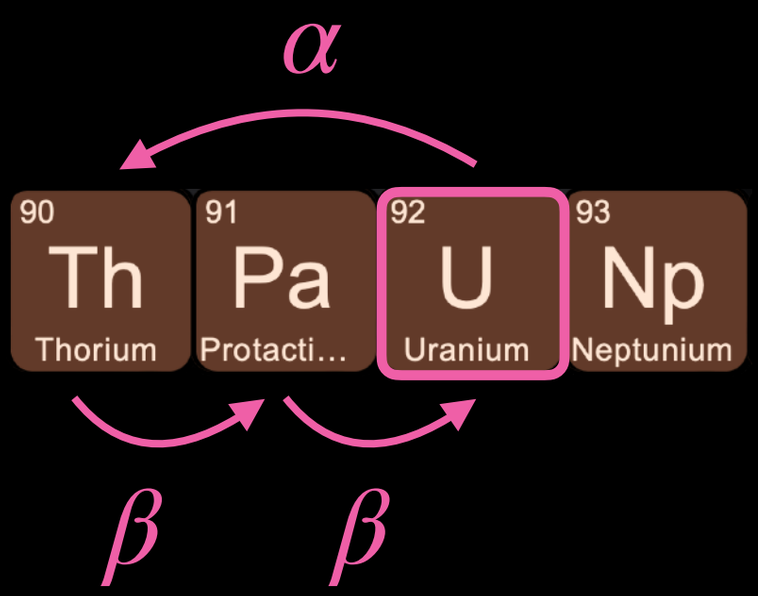


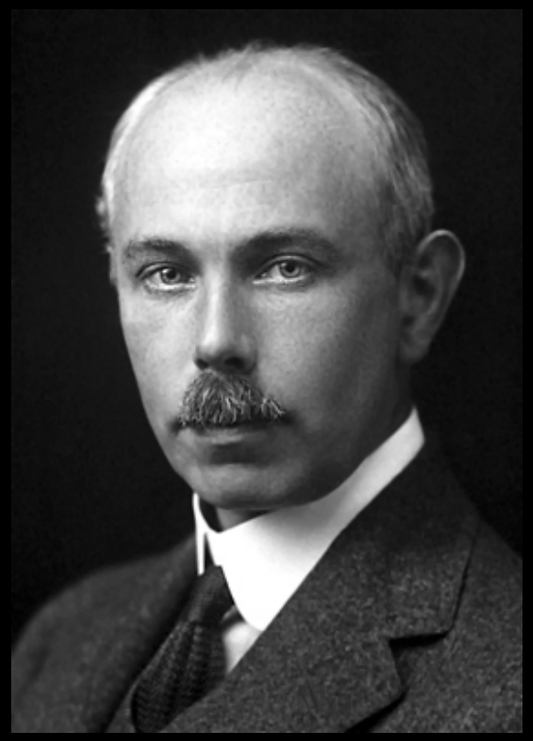
Hydrogen

Adding more and more electrons *(and protons)* builds up the elements in the periodic table

Another hint from chemistry

Can chemical elements exist “multiple times”?



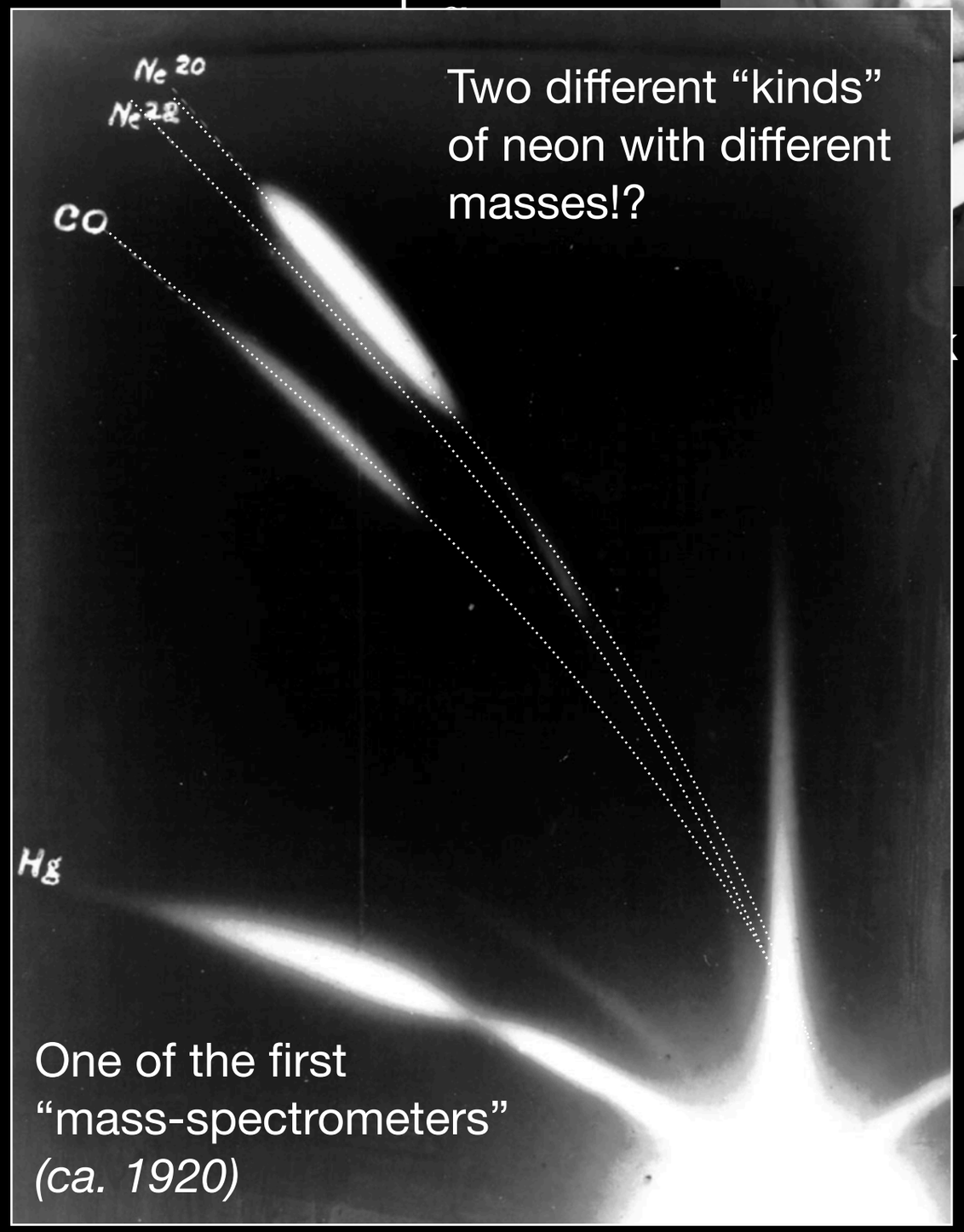


J.J. Thomson

Francis Aston

Uranium

Soddy



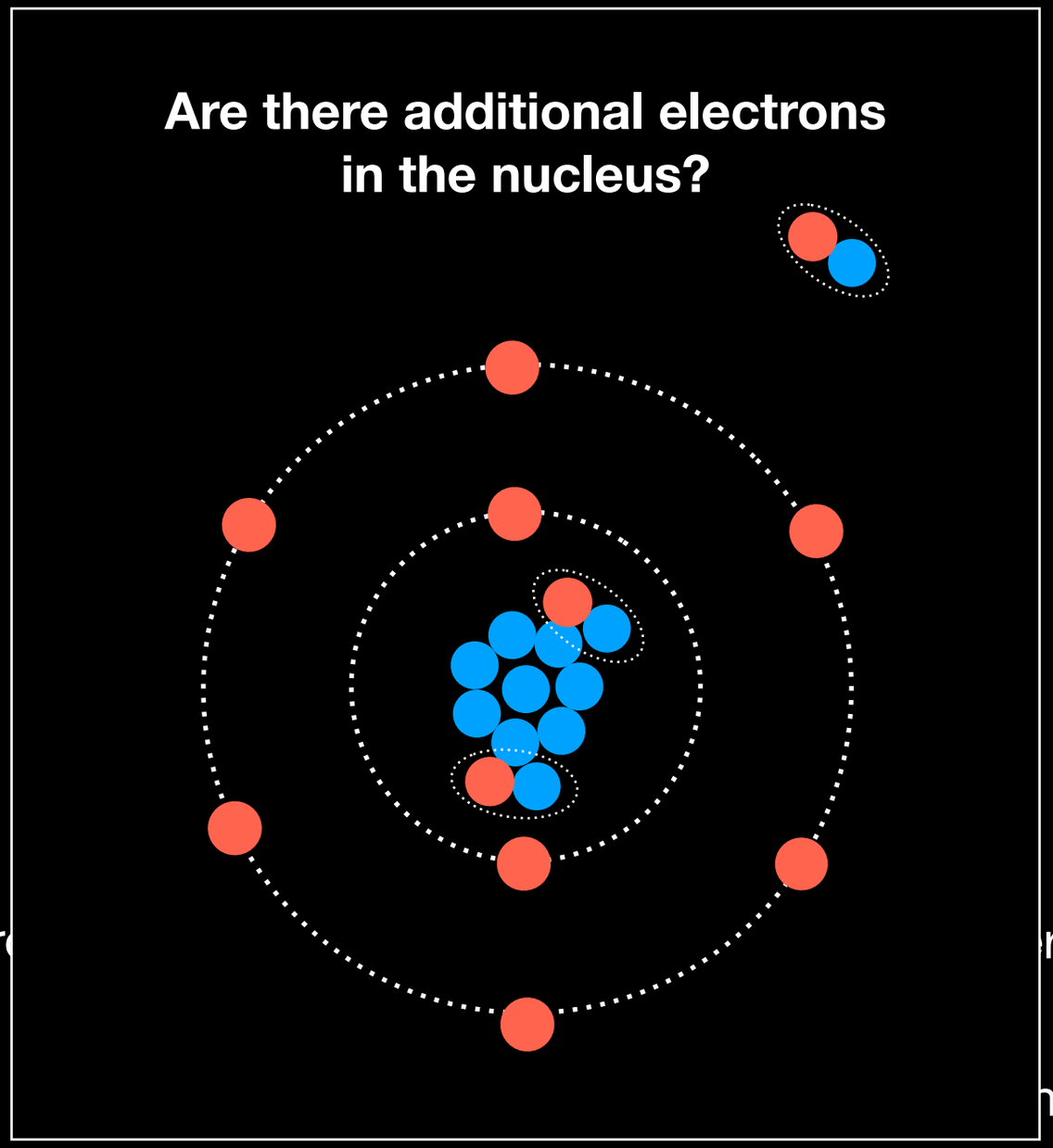
Two different “kinds” of neon with different masses!?

One of the first “mass-spectrometers” *(ca. 1920)*

How is this possible?

Proton

Electron



But: adding another pr r) element …

n of the same element!

What's wrong?

A new neutral particle?

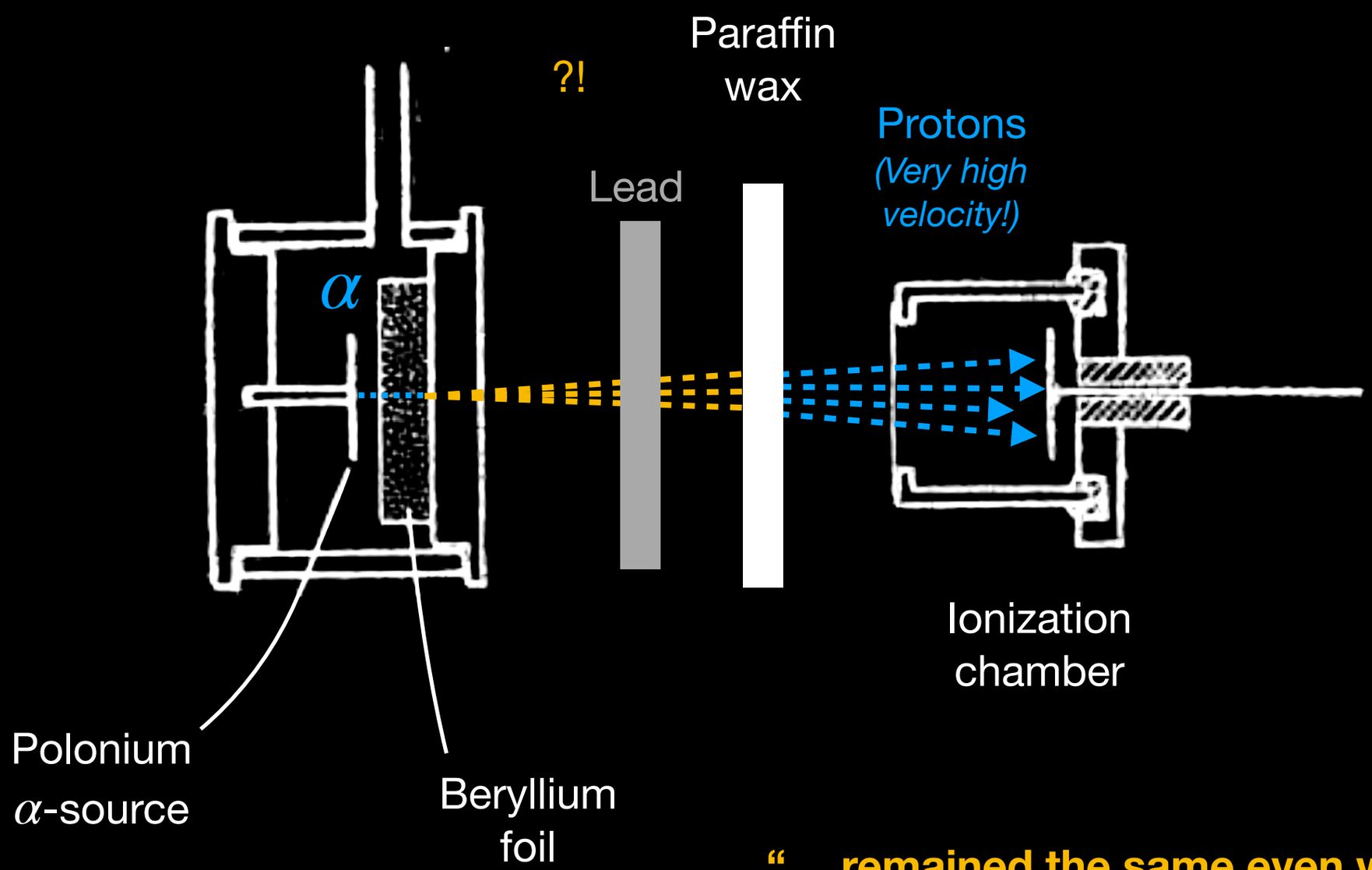
1932

James Chadwick

Frédéric and Irène Joliot-Curie

A new particle?

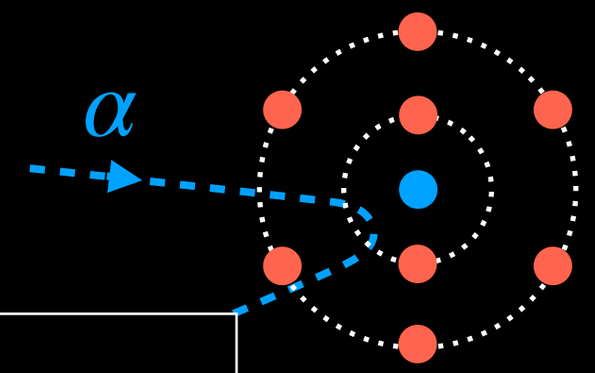
1932



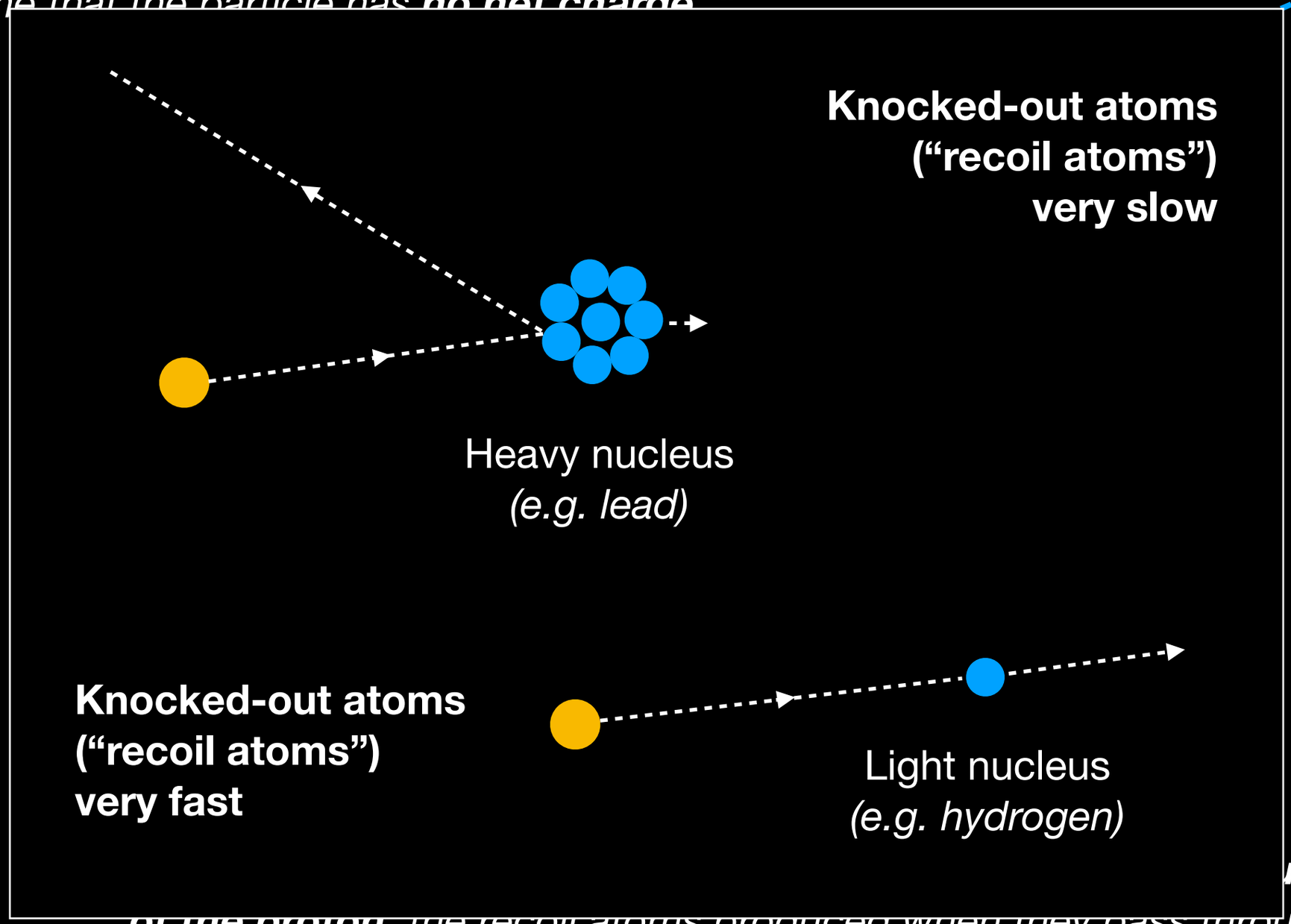
"… remained the same even when as much as 2 cm of lead were inserted …"

→ *very penetrating radiation*

A new neutral particle?



*"In order to explain the great penetrating power of the radiation we must assume that the particle has **no net charge**."*



ual to that
***of the proton**, the recoil atoms produced when they pass through matter containing hydrogen will have high velocities."*

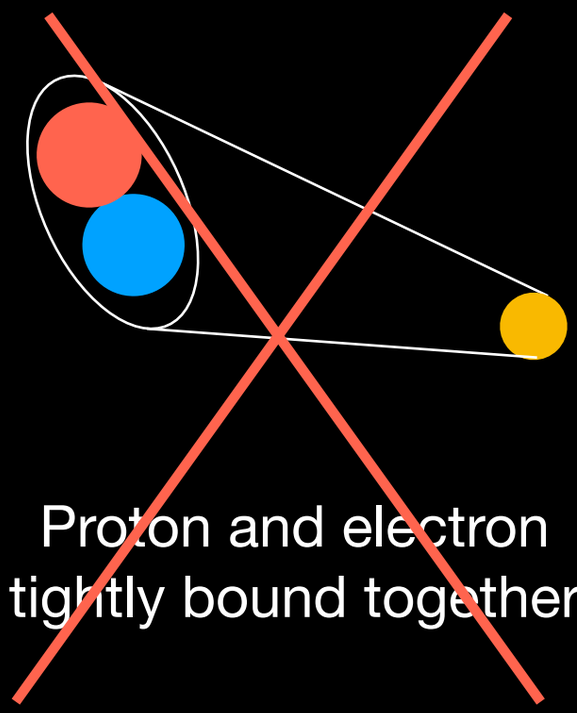
Which kind of neutral particle?

Chadwick (1932):

"It is concluded that the radiation consists of neutrons, particles of mass 1, and charge 0."

(The Joliot-Curies missed a major discovery!)

But what kind of neutron?



Proton and electron tightly bound together

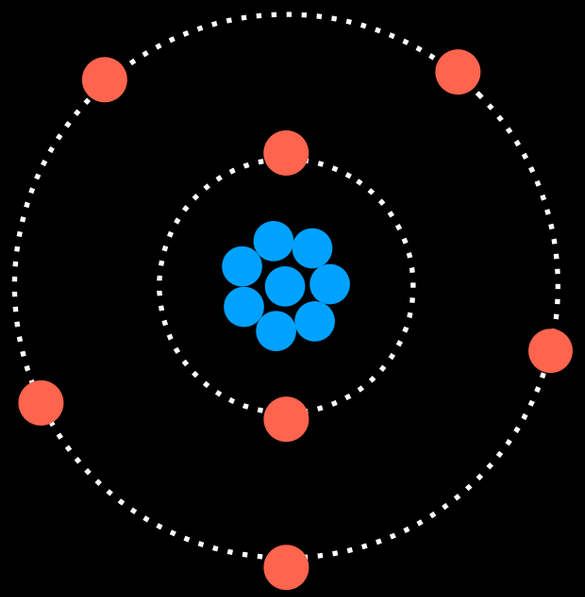
New particle without building blocks

Chadwick + Goldhaber (1935):

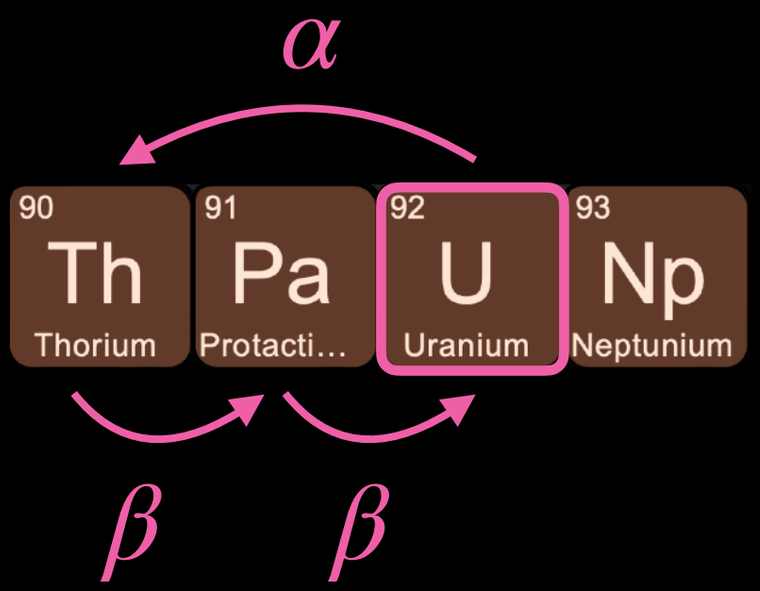
Mass of neutron larger than proton and electron taken together!

An updated view of the atom

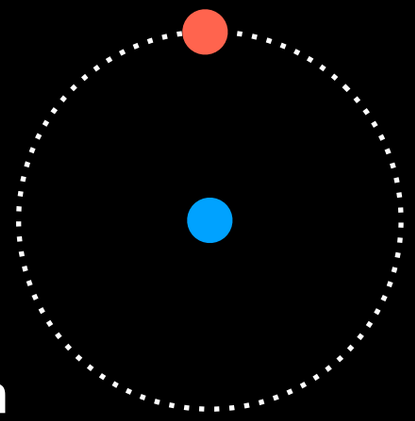
- Proton
- Neutron
- Electron



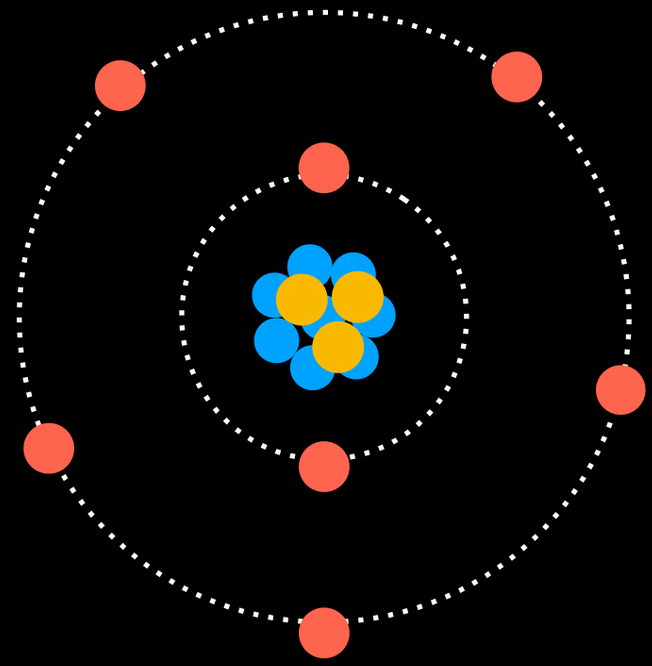
Nitrogen
(Heavier than hydrogen)



Soddy's "different kinds of uranium" contain different numbers of neutrons!



Hydrogen



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