THE UNIVERSITY OF CHICAGO

ENRICO FERMI INSTITUTE

HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

Additional Material

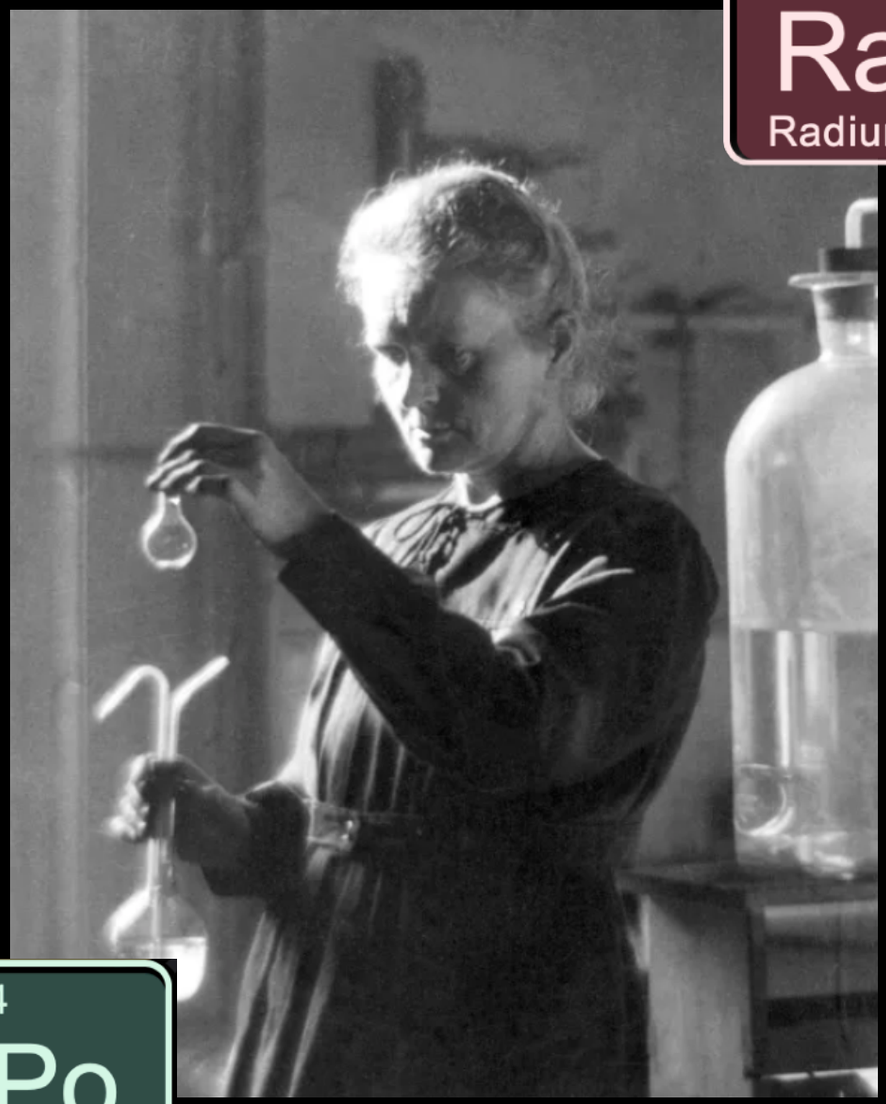
Philipp Windischhofer

November 18, 2023

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

The discovery of radioactivity

Henri Becquerel *(1896)*



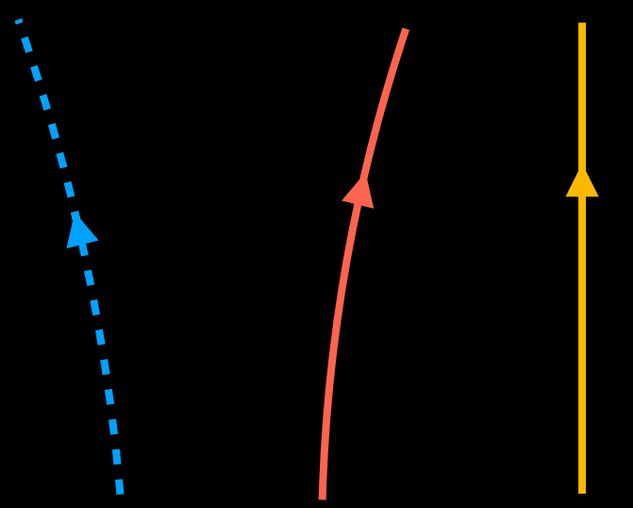
88
Ra
Radium

84
Po
Polonium

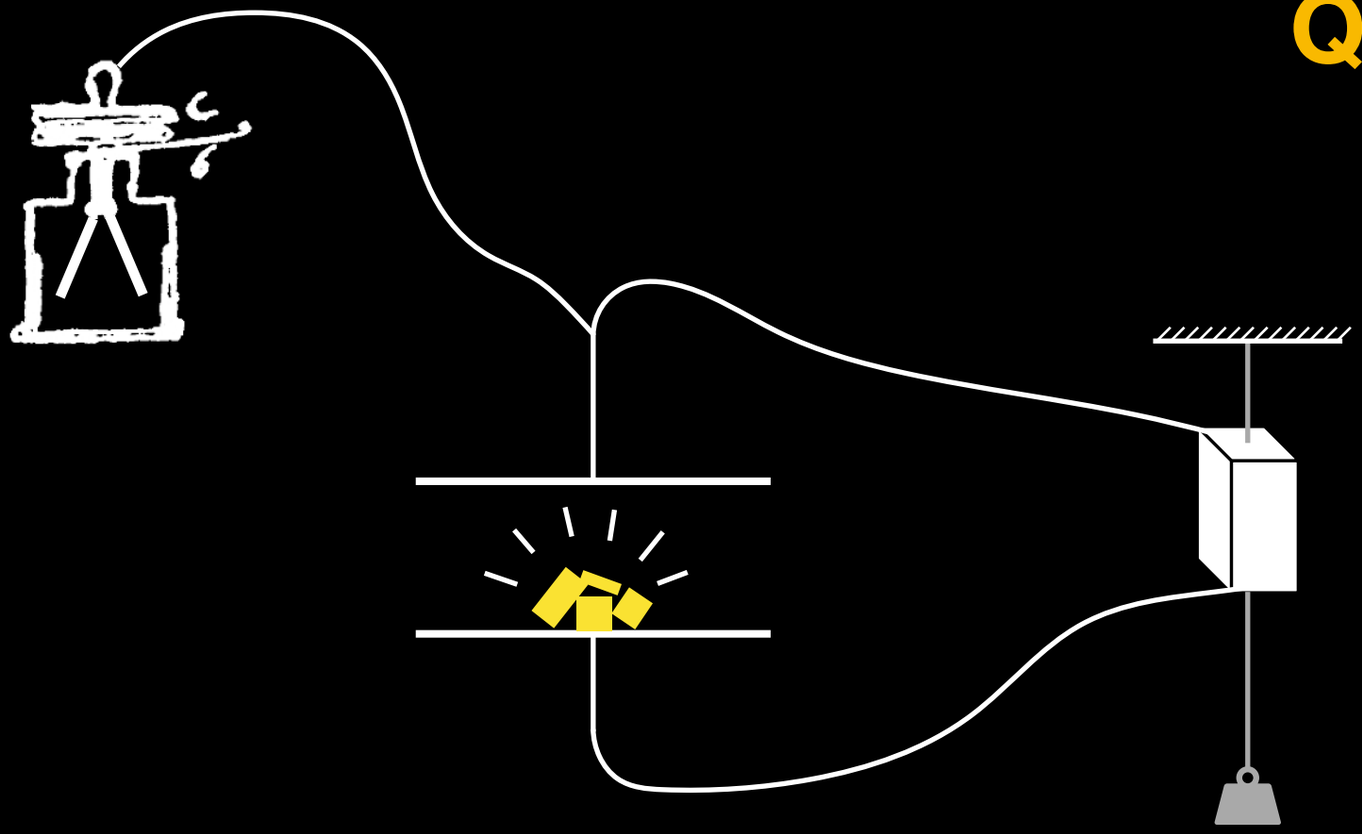
Marie Skłodowska-Curie
Pierre Curie
(1898)

Ernest Rutherford
Paul Villard
(1903)

α β γ



Quantifying radioactivity

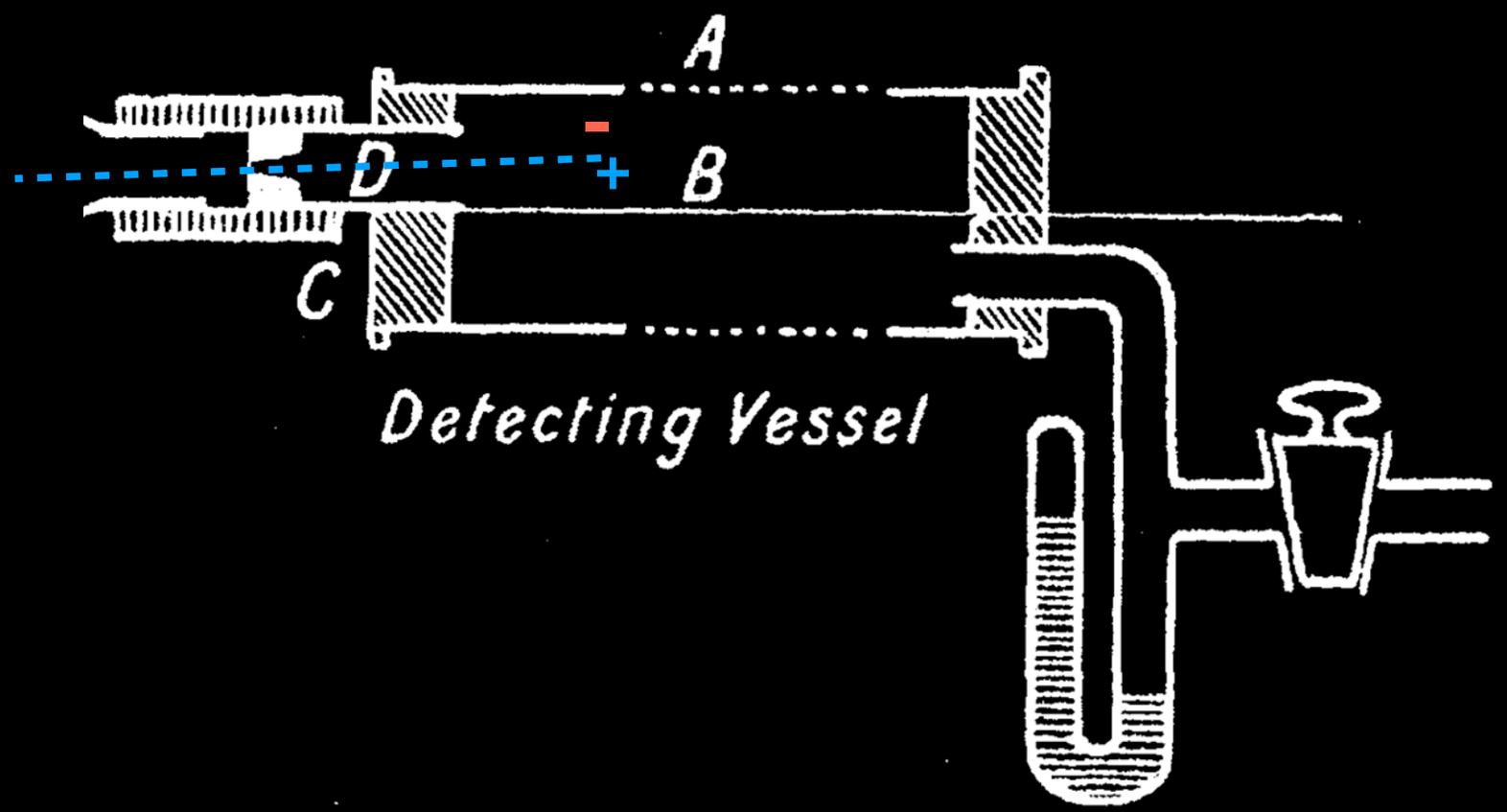


Precision ionisation chamber

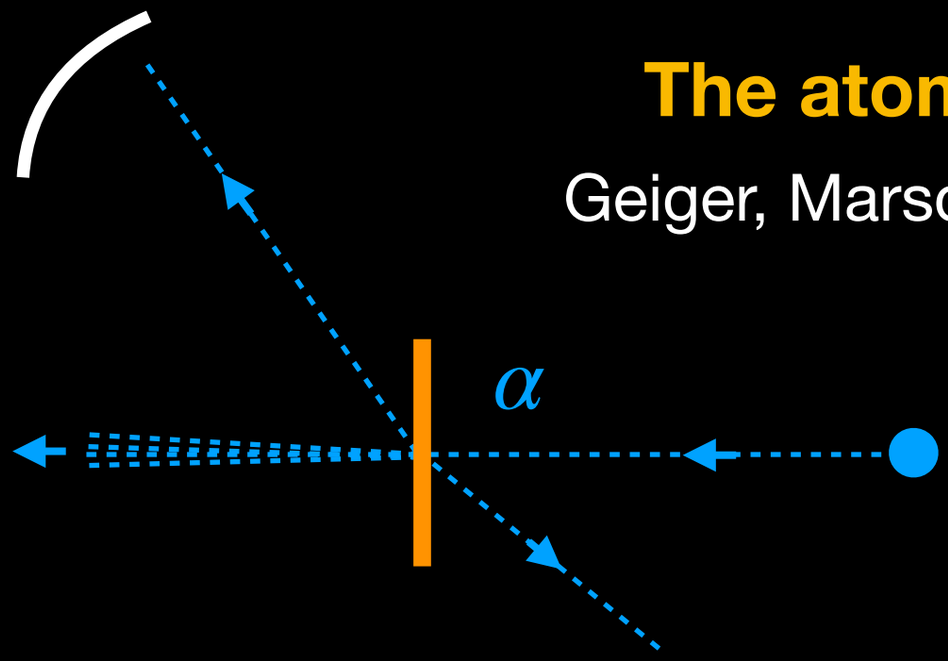
“Curie method”

α-particle counter

Geiger and Rutherford

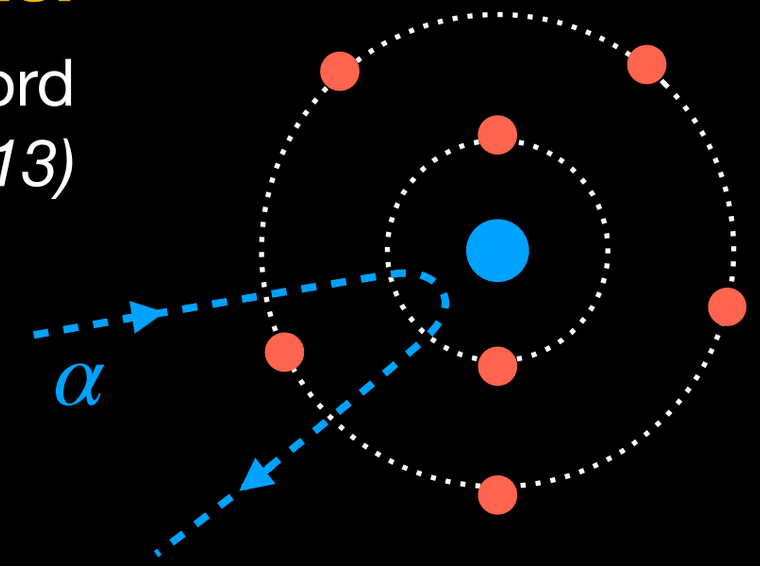


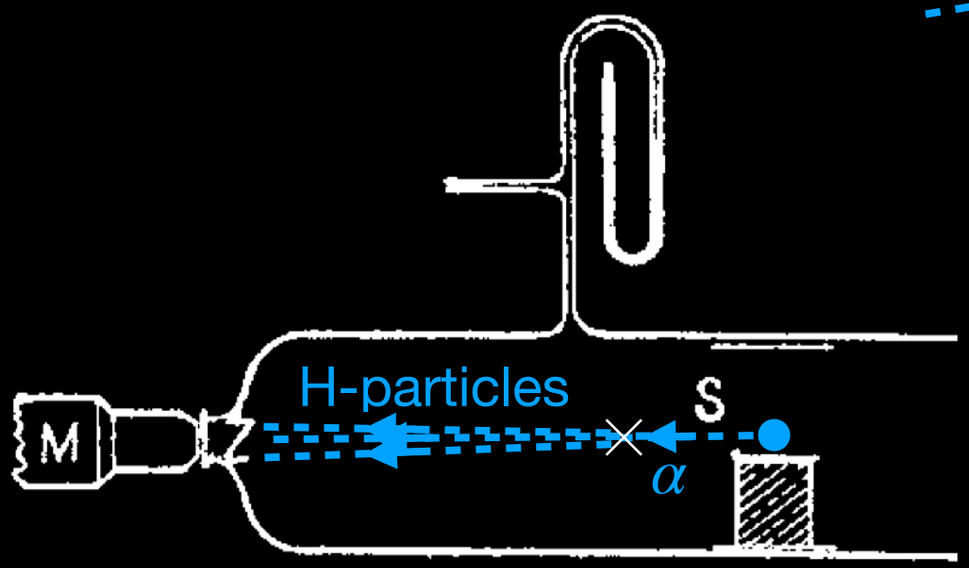
A tool for discovery

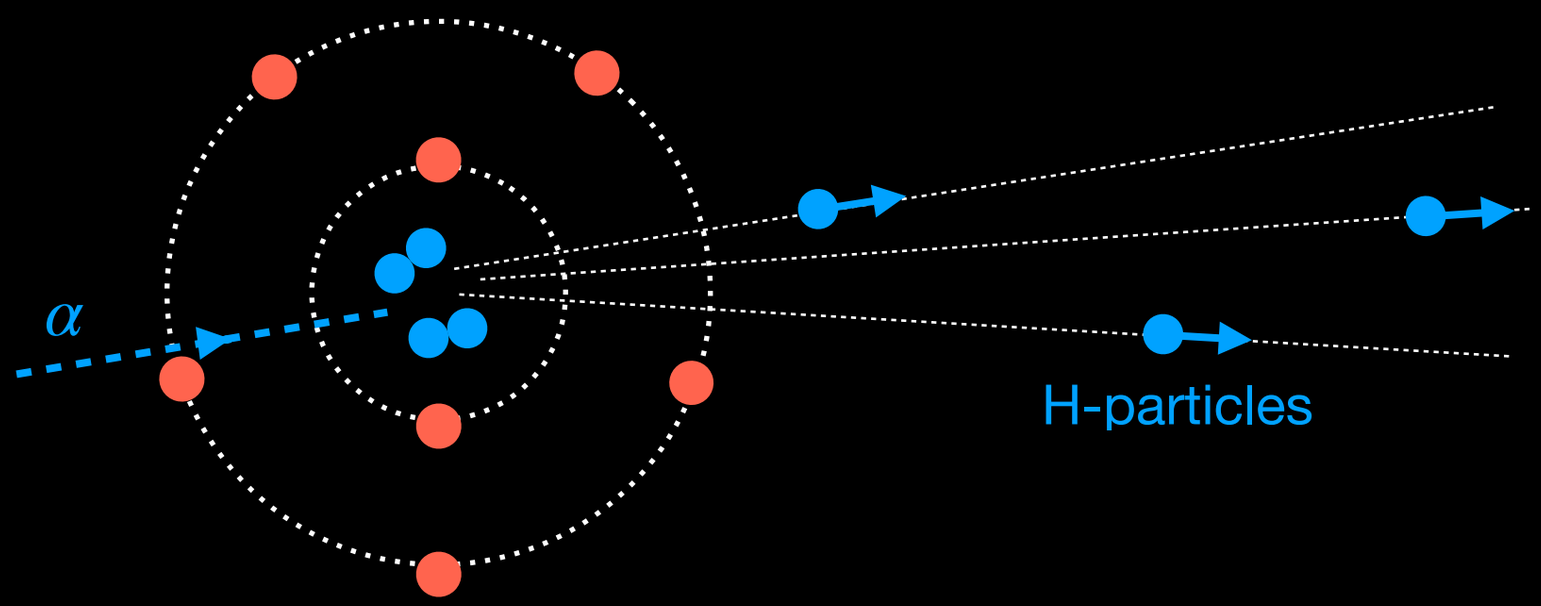


The atom has a nucleus!

Geiger, Marsden, and Rutherford *(1913)*



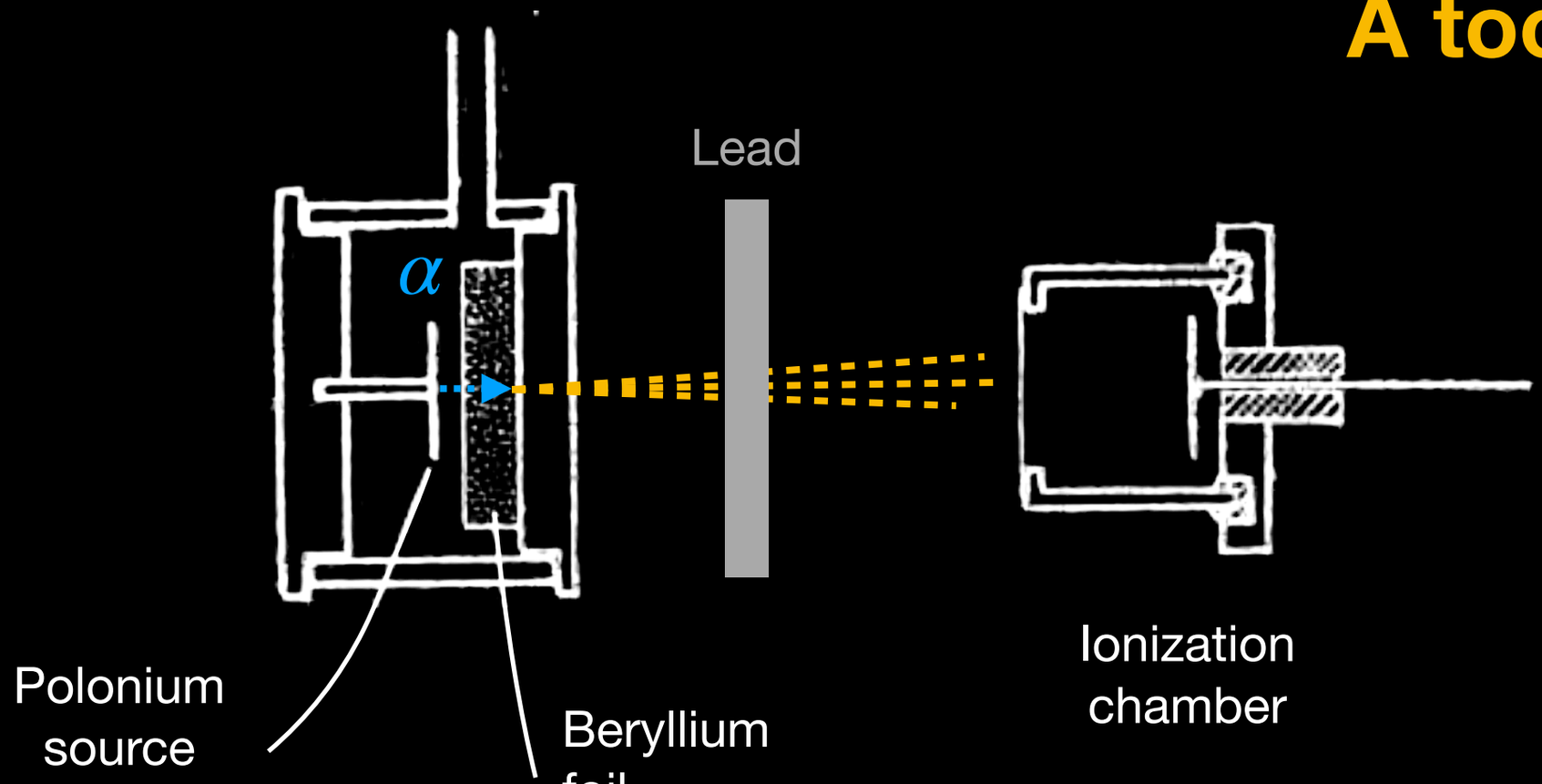




The nucleus consists of protons!

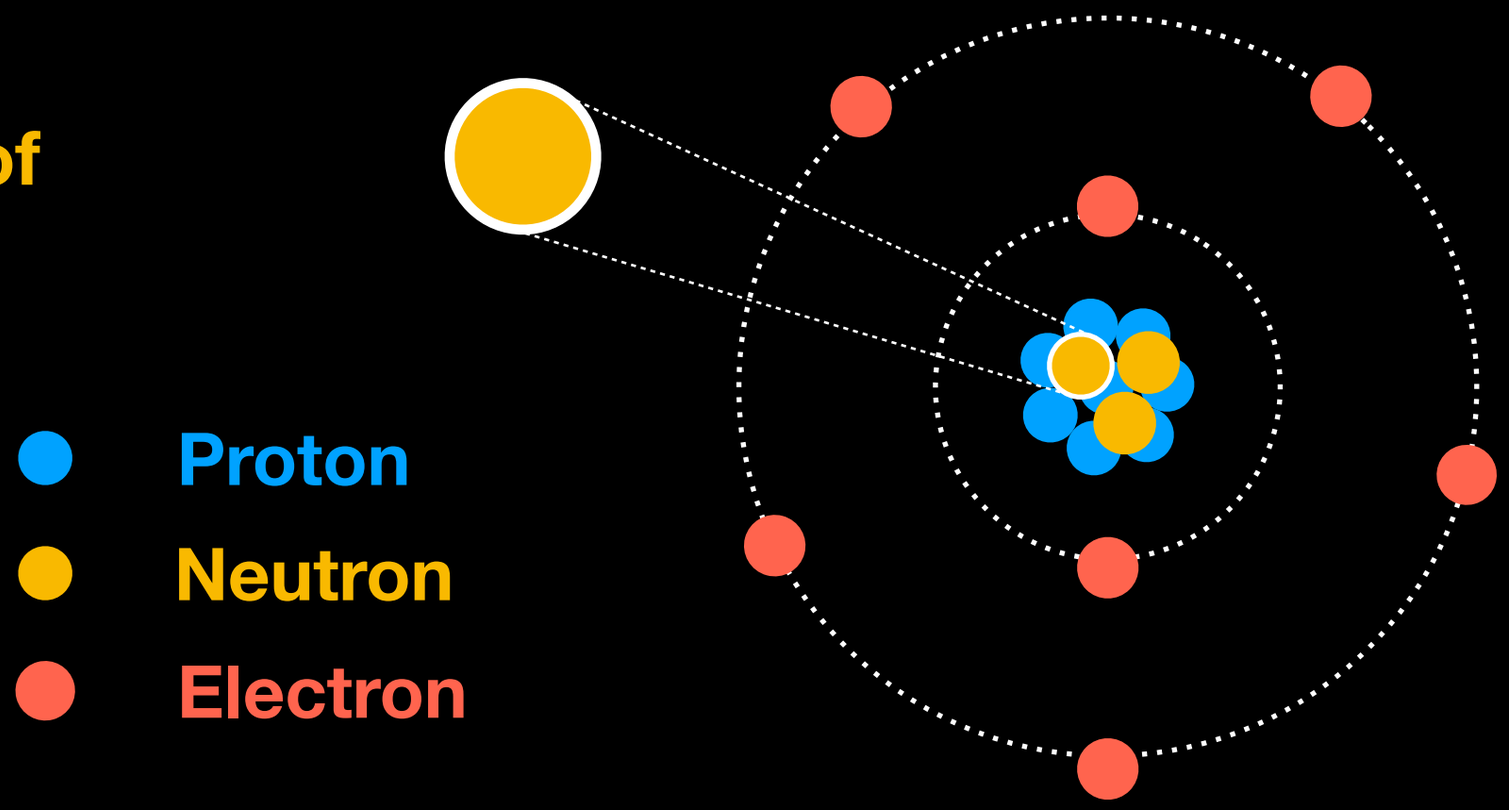
Marsden and Rutherford *(1919)*

A tool for discovery



James Chadwick
(1932)

The nucleus consists of protons and neutrons!

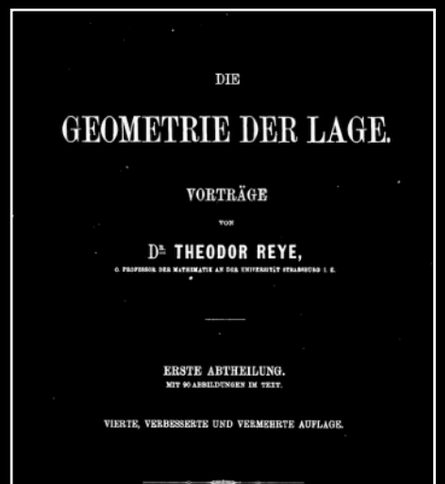


Proton

Neutron

Electron

Enrico Fermi


DIE

GEOMETRIE DER LAGE.

VORTRÄGE

VON

Dr. THEODOR REYE,

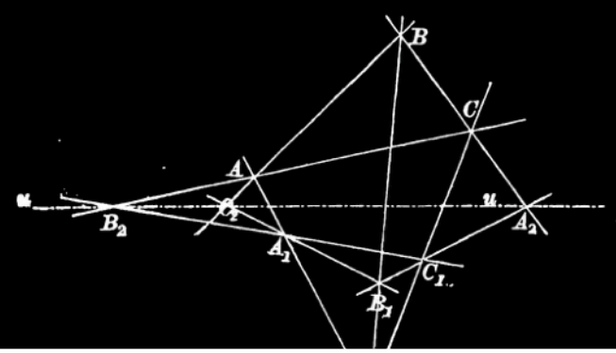
O. PROFESSOR DER MATHEMATIK AN DER UNIVERSITÄT STRASSBURG I. E.

ERSTE ABTHEILUNG.

MIT 90 ABBILDUNGEN IM TEXT.

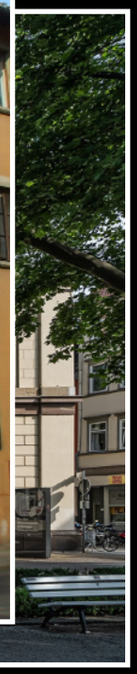
VIERTE, VERBESSERTE UND VERMEHRTE AUFLAGE.

Geometry: his gateway into science



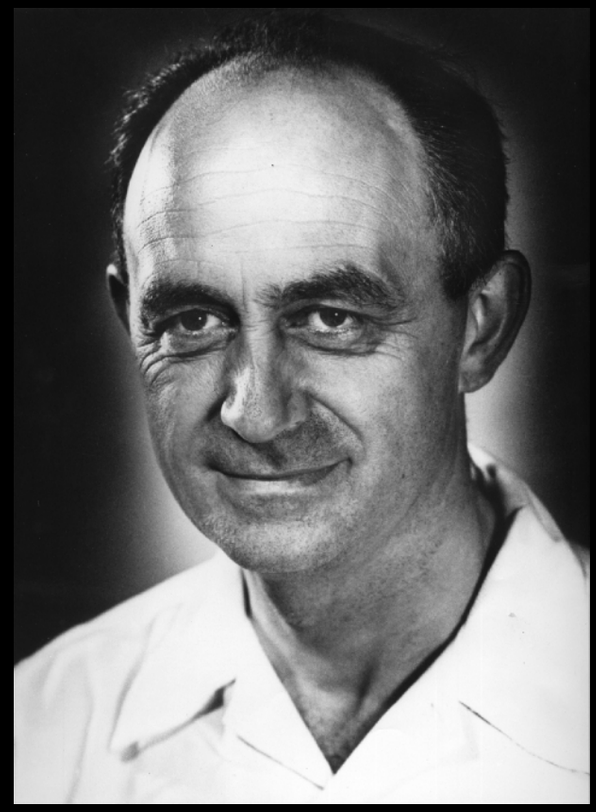
Leiden

Florence



ettingen

Pisa



"I can calculate anything in physics within a factor 2 on a few sheets; to get it fully right may well take a physicist a year, but I am not interested in that."

Back in Rome: the Via Panisperna boys

Orso Corbino
“God almighty”

Edoardo Amaldi
“The Young Boy”

Franco Rasetti
“The Cardinal Vicar”

“The pope”

News from Paris: artificial radioactivity

Frédéric and
Irène Joliot-Curie

1934

"Our latest experiments have shown a very striking fact."

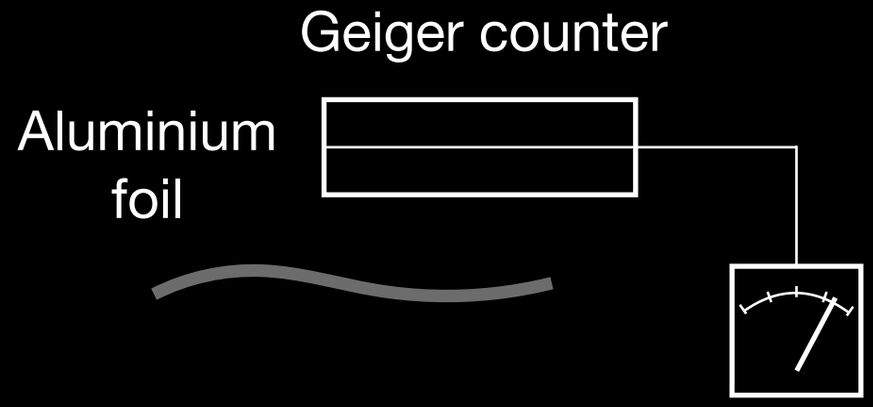
"When an aluminium foil is irradiated on a polonium preparation …"

News from Paris: artificial radioactivity

Frédéric and
Irène Joliot-Curie

1934

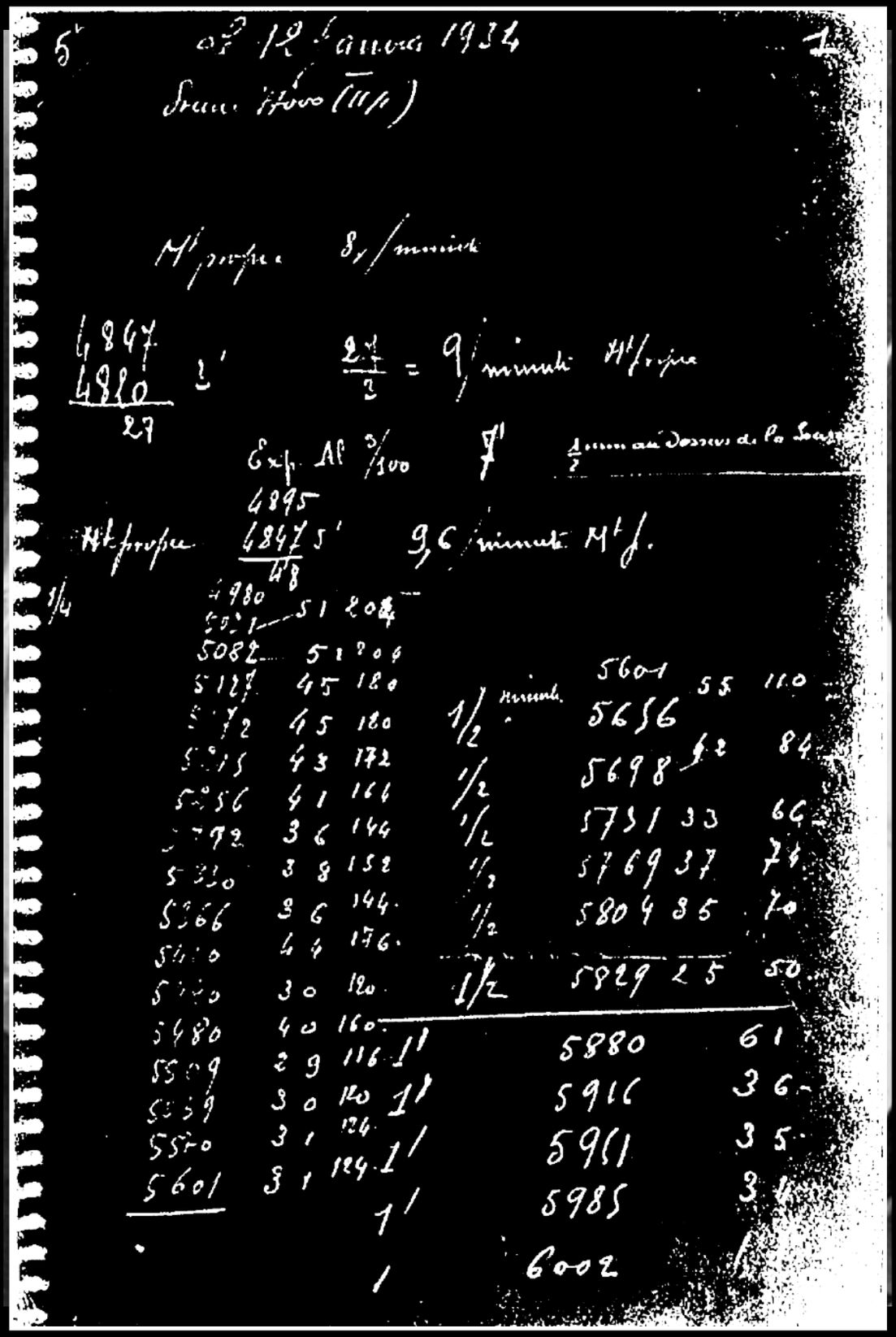
"Our latest experiments have shown a very striking fact."



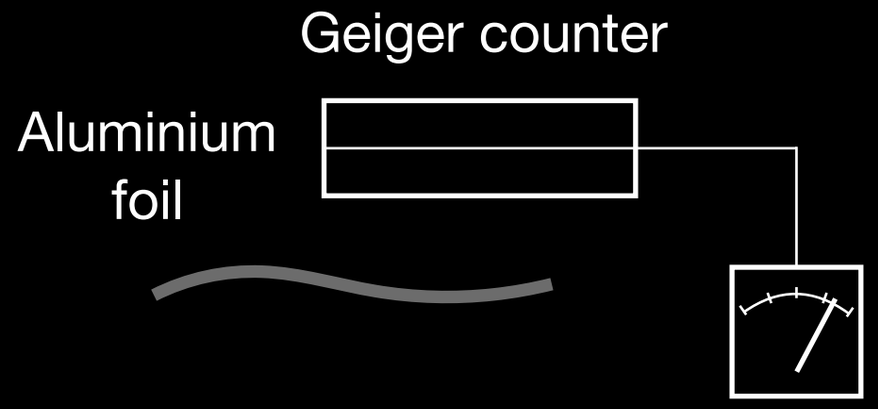
Polonium
α-source

"… the emission of radiation does not cease immediately when the active preparation is removed."

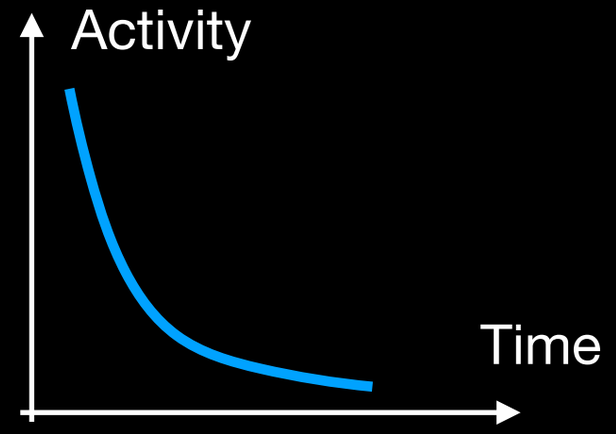
News from Paris: artificial radioactivity



"Our latest experiments have shown a very striking fact."



Polonium
α-source

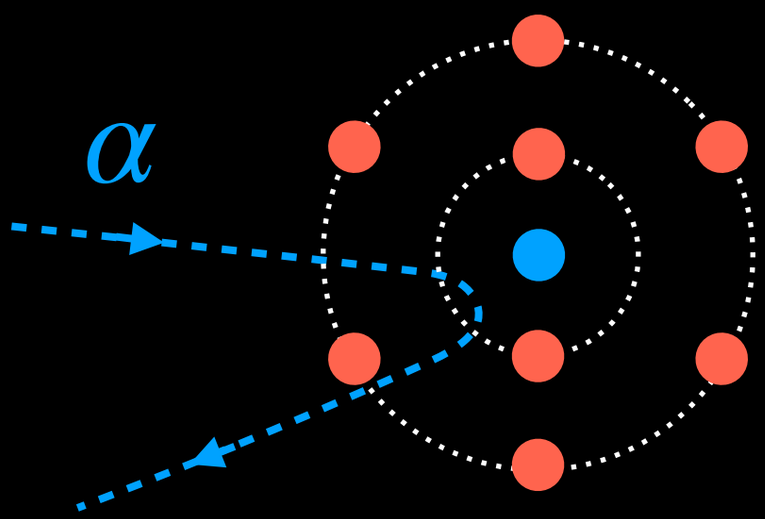


"The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element."

Back to Rome

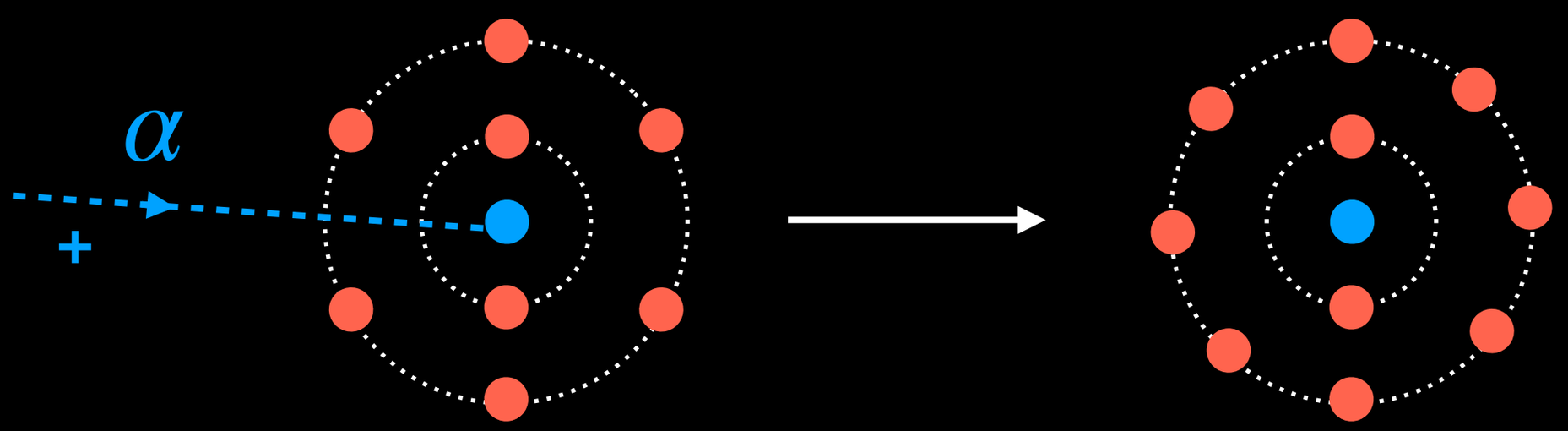
Artificial Production of a New Kind of Radio-Element

By F. Joliot and I. Curie, Institut du Radium, Paris



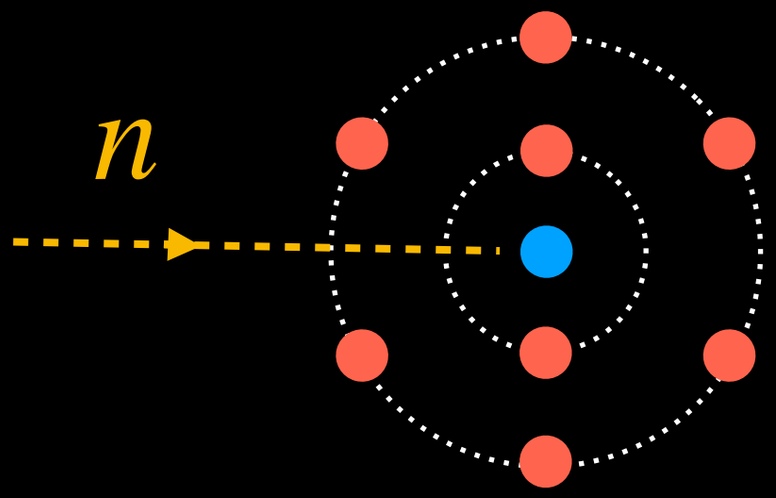
Fermi: High-intensity α-source,
but most α-particles do not reach the nucleus!

Aluminium atom



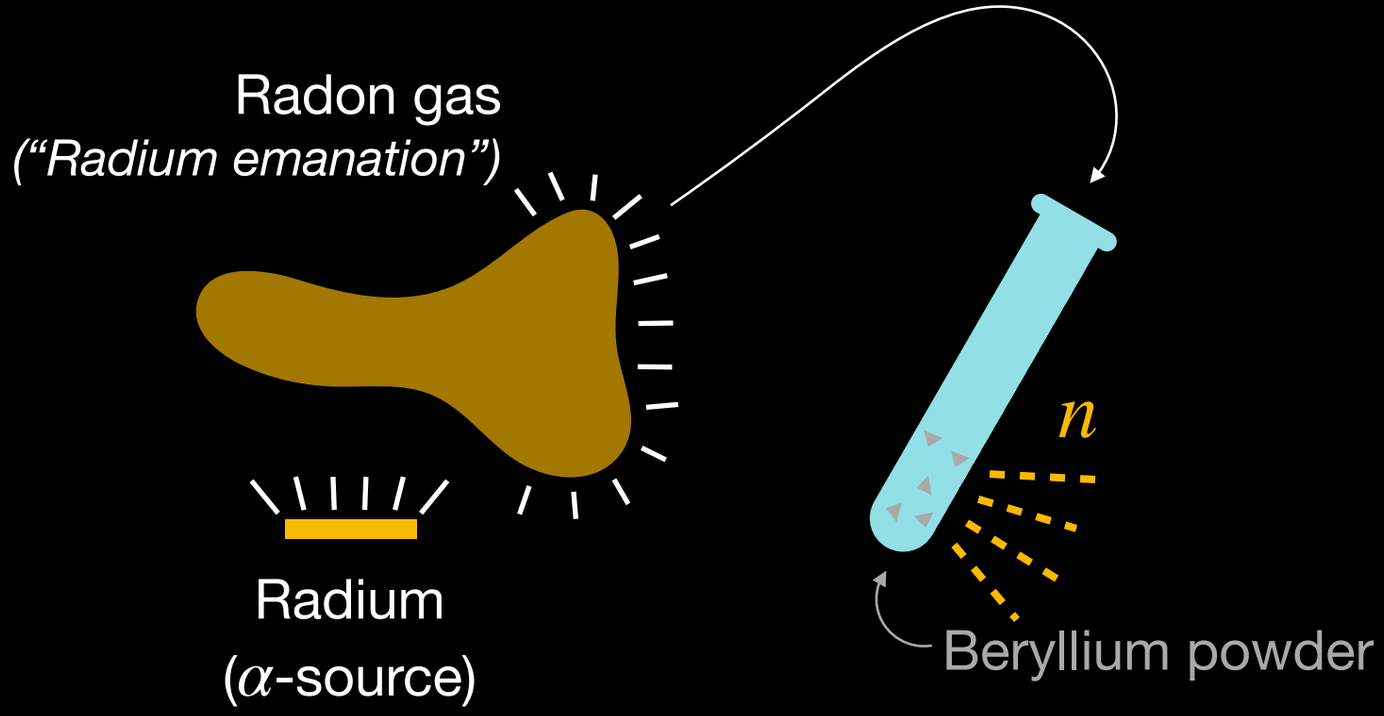
Phosphorus atom

What about neutrons?



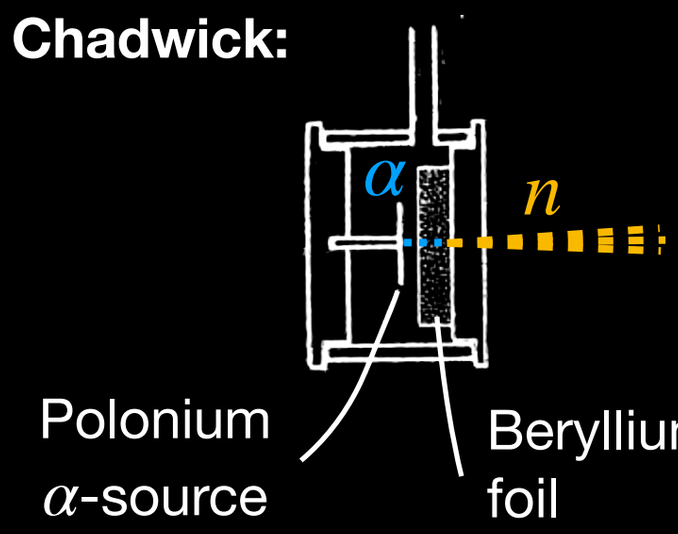
Fermi: Uncharged neutrons would not get deflected!

But: available neutron sources much weaker
(Chadwick and Rutherford also in the game!)



*(Institute of Public Health,
Via Panisperna basement)*

Chadwick:



Neutron-induced radioactivity

So far, we have obtained an effect with the following elements :

Phosphorus—Strong effect. Half-period about 3 hours. The disintegration electrons could be photographed in the Wilson chamber. Chemical separation of the active product showed that the unstable element formed under the bombardment is probably silicon.

Iron—Period about 2 hours. As the result of chemical separation of the active product, this is probably manganese.

Silicon—Very strong effect. Period about 3 minutes. Electrons photographed in the Wilson chamber.

Aluminium—Strong effect. Period about 12 minutes. Electrons photographed in the Wilson chamber.

Chlorine—Gives an effect with a period much longer than that of any element investigated at present.

Vanadium—Period about 5 minutes.

Copper—Effect rather small. Period about 6 minutes.

Arsenic—Period about two days.

Silver—Strong effect. Period about 2 minutes.

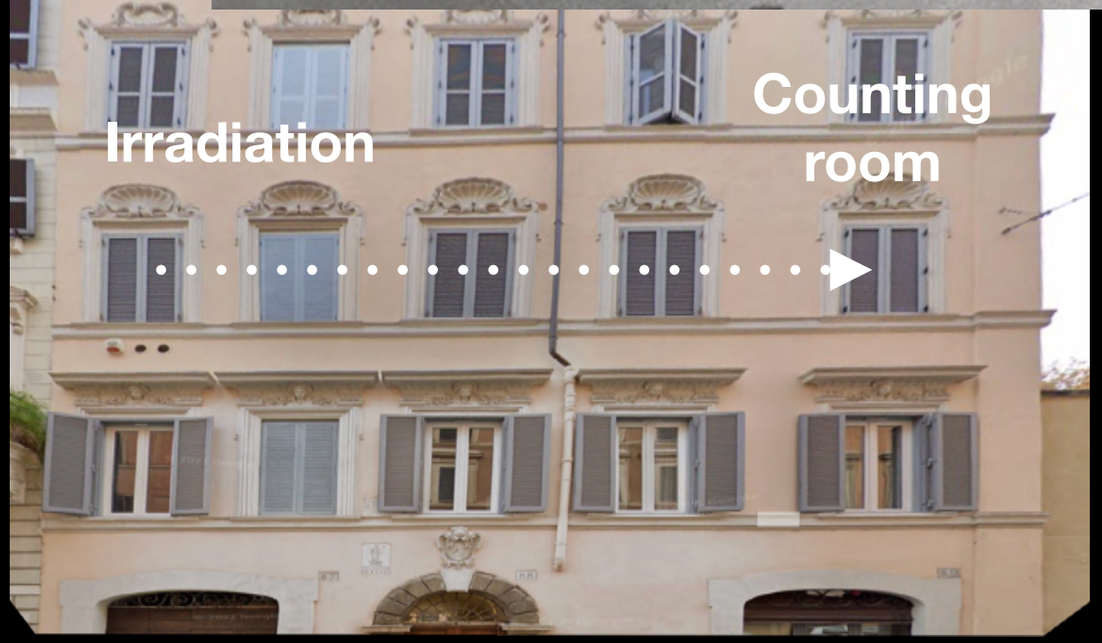
Tellurium—Period about 1 hour.

Iodine—Intense effect. Period about 30 minutes.

Chromium—Intense effect. Period about 6 minutes. Electrons photographed in the Wilson chamber.

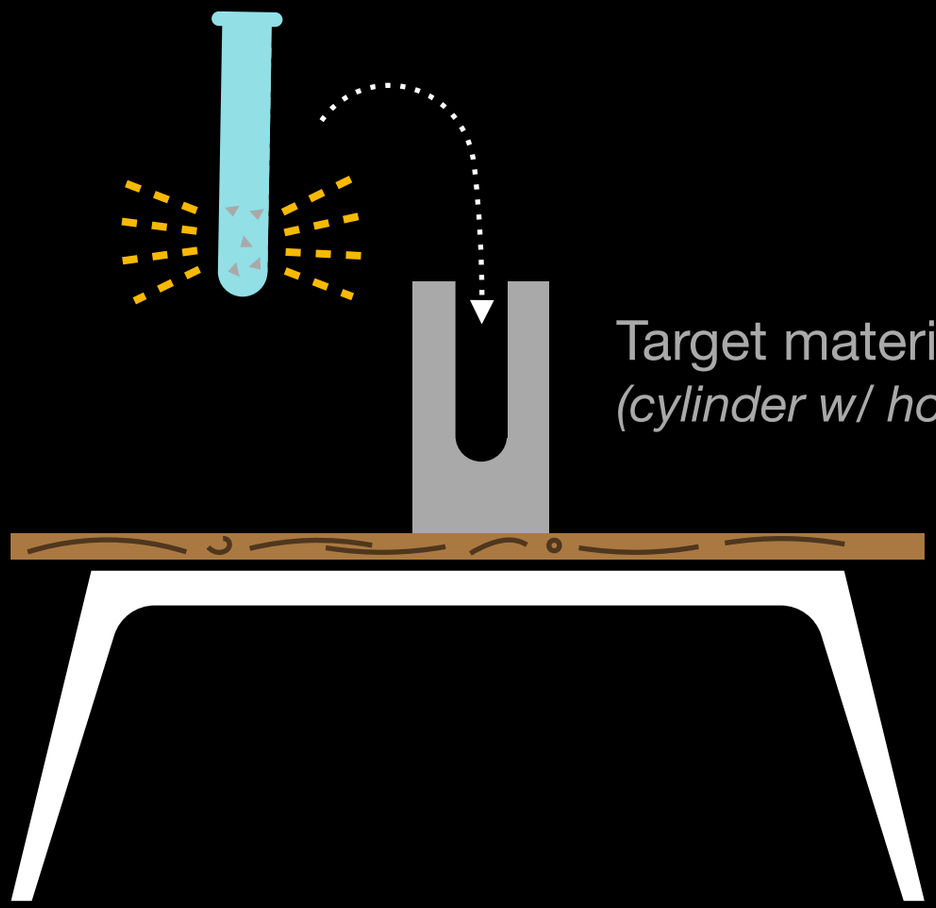
Barium—Small effect. Period about 2 minutes.

Fluorine—Period about 10 seconds.

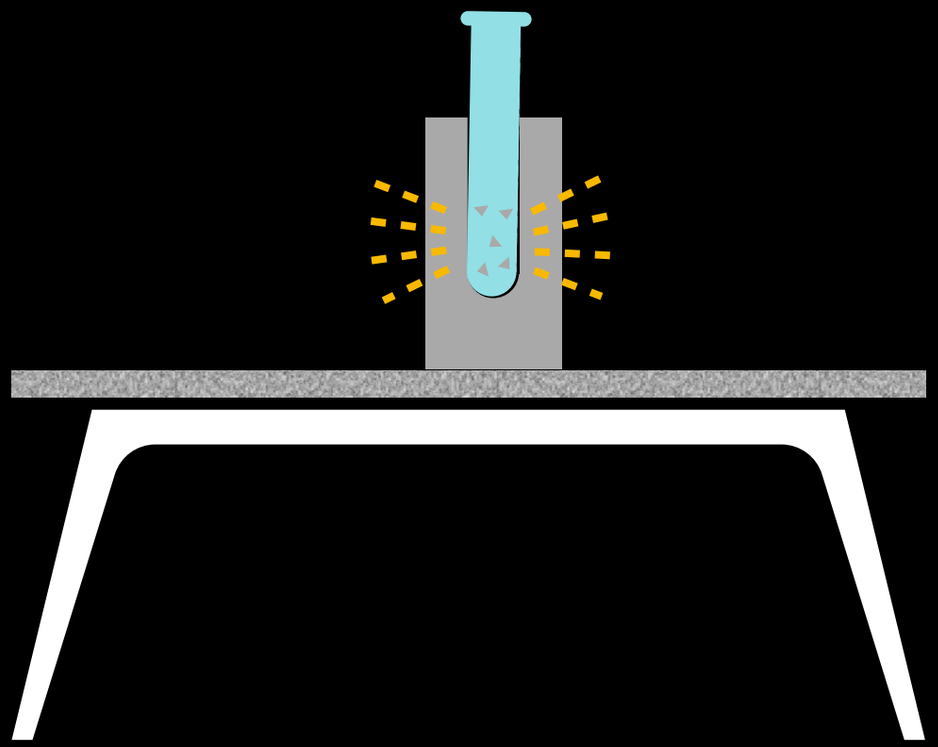


The results were not reproducible!

Wanted to use silver as “activation standard” to compare against



Wooden table



Marble table

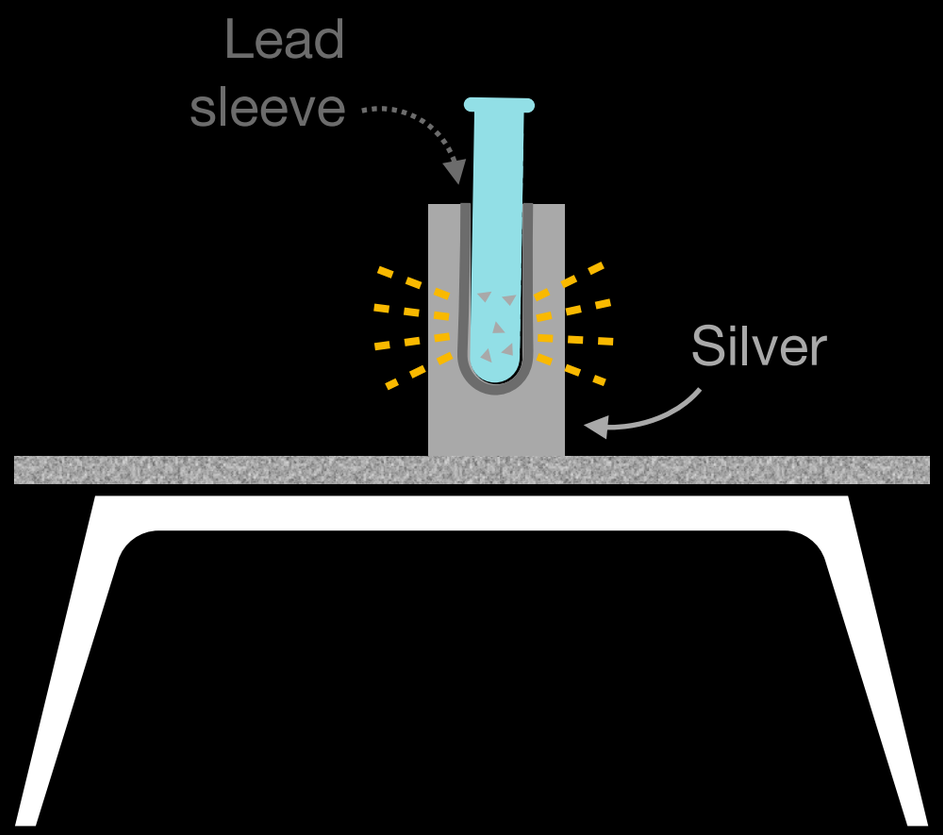
Much stronger effect for wood!

Fermi's discovery

"We were working very hard in the neutron-induced radioactivity and the results we were obtaining made no sense."

"One day, as I came to the laboratory, it occurred to me that I should examine the effect of placing a piece of lead before the incident neutrons."

"I took great pains to have the piece of lead precisely machined."

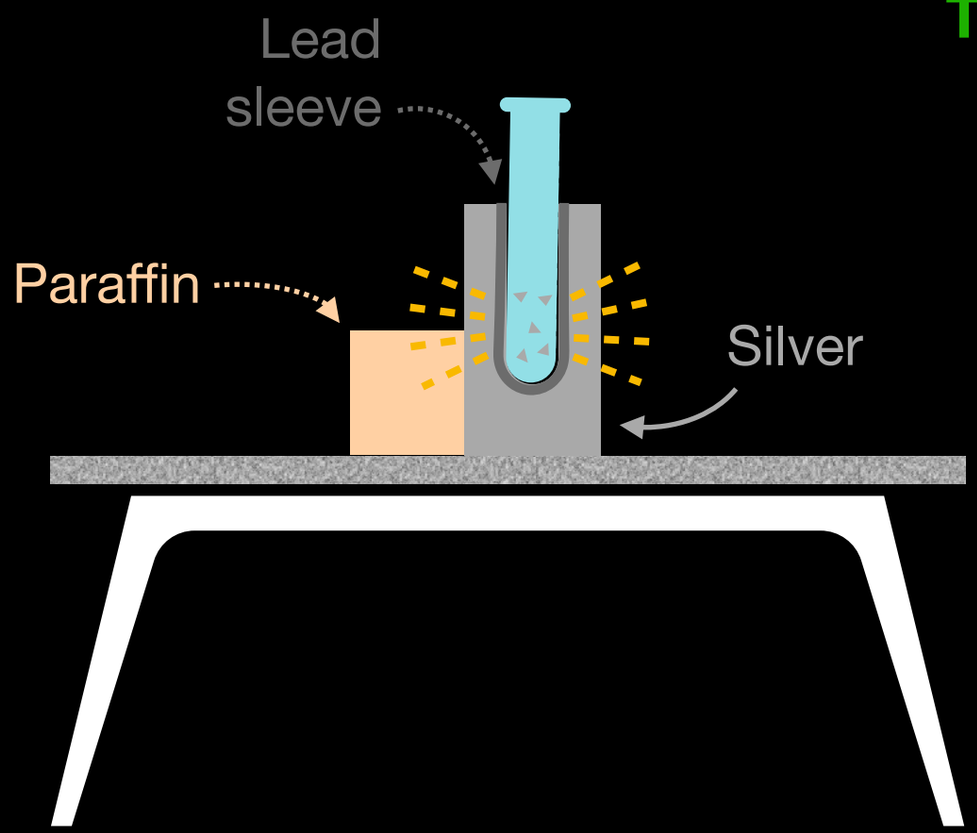


Fermi's discovery

"We were working very hard in the neutron-induced radioactivity and the results we were obtaining made no sense."

"I tried every excuse to postpone putting the piece of lead in its place."

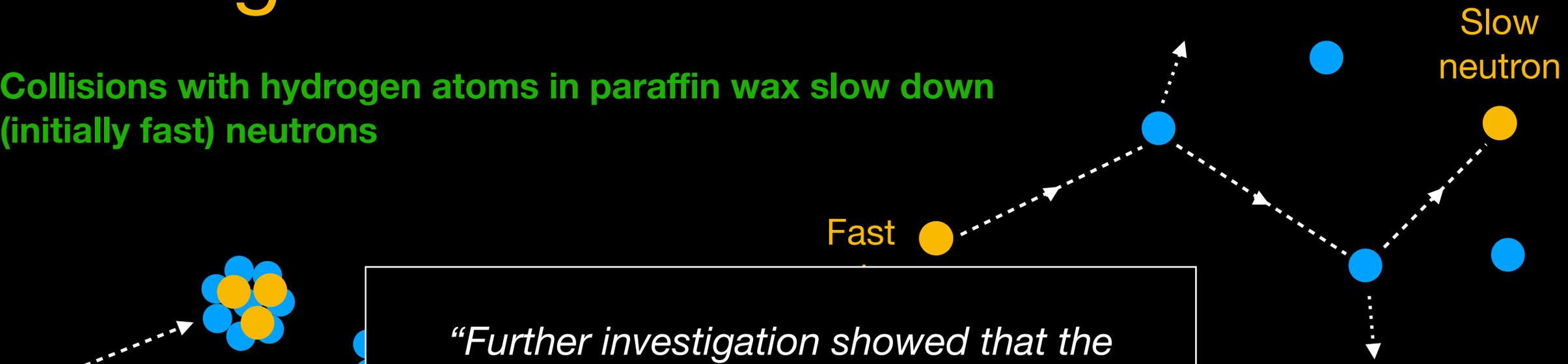
"When finally, with some reluctance, I was going to put it in its place, I said to myself, 'No, I don't want this piece of lead here; what I want is a piece of paraffin.'"



The activation became a lot stronger!

Slowing down neutrons

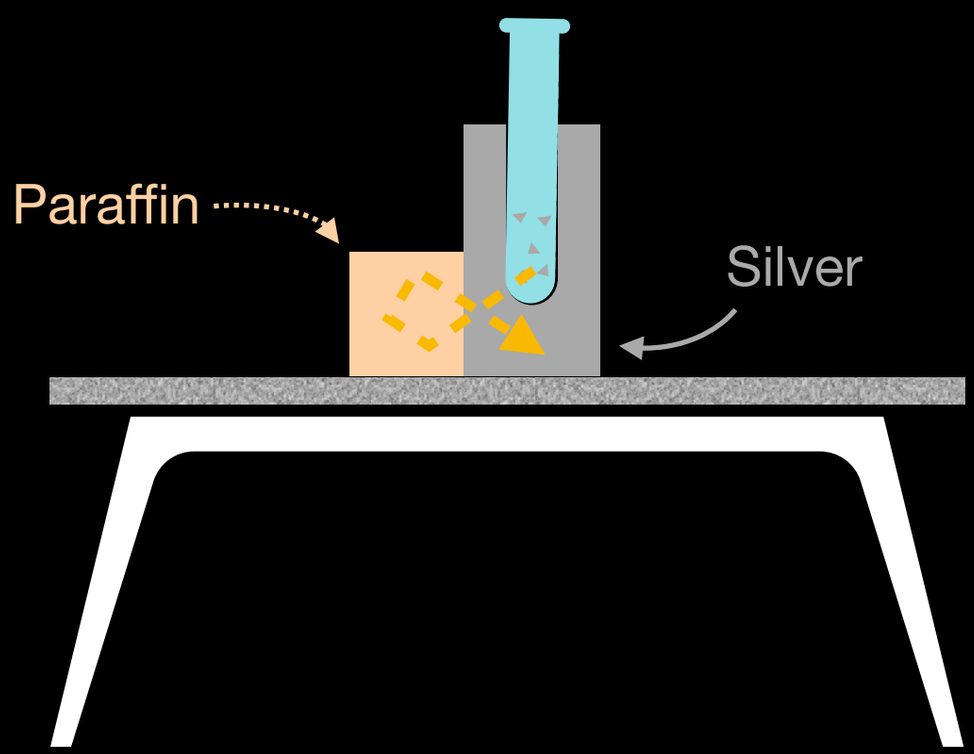
Collisions with hydrogen atoms in paraffin wax slow down (initially fast) neutrons

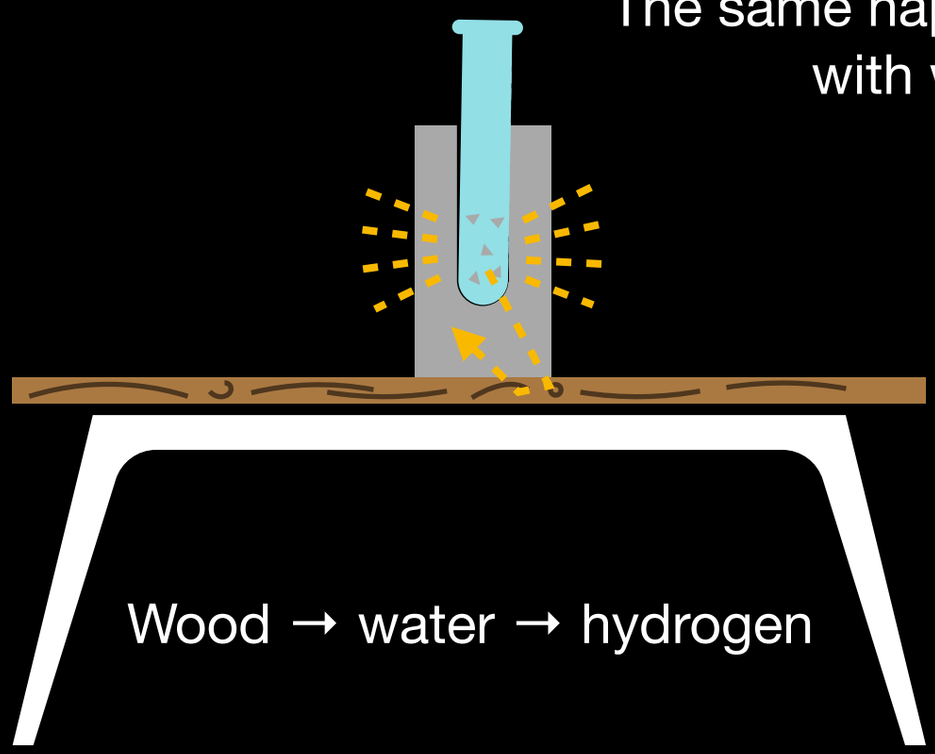


"Further investigation showed that the activation could be enormously increased by surrounding the source and the activated substance with a large amount of water or paraffin wax."

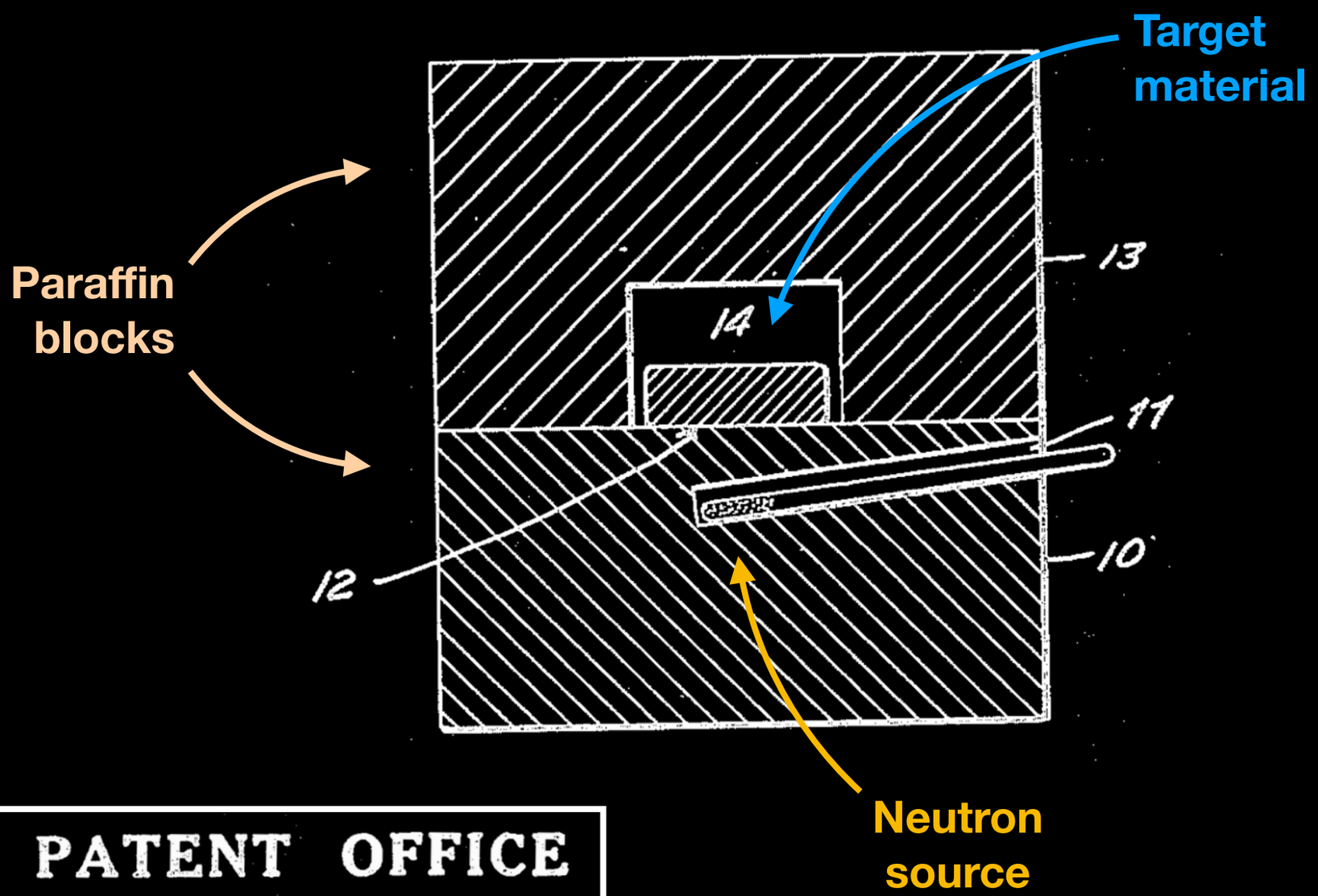
the target nucleus

The same happens with wood!





Patenting slow neutrons



UNITED STATES PATENT OFFICE

2,206,634

PROCESS FOR THE PRODUCTION OF RADIOACTIVE SUBSTANCES

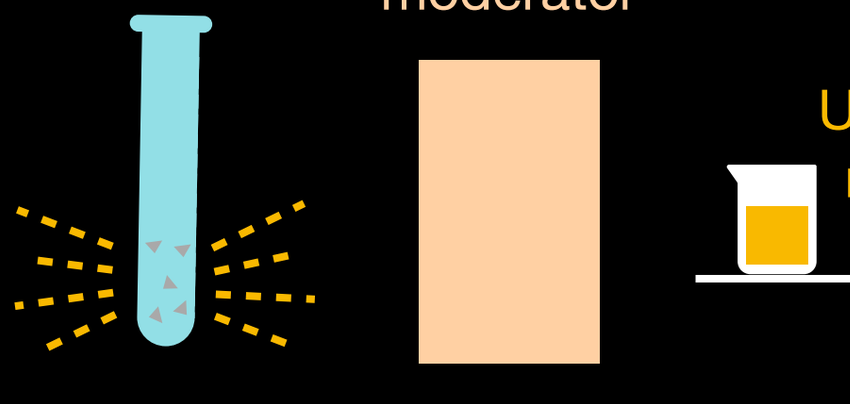
Enrico Fermi, Edoardo Amaldi, Bruno Pontecorvo, Franco Rasetti, and Emilio Segre, Rome, Italy, assignors to G. M. Giannini & Co., Inc., New York, N. Y., a corporation of New York

Application October 3, 1935, Serial No. 43,462
In Italy October 26, 1934

7 Claims. (Cl. 204—31)

Fermi's blunder

Exposing uranium to "thermal" neutrons



Chemical separation:

- ✗ Uranium (92 protons)
- ✗ Palladium (91 protons)
- ✗ Thorium (90 protons)
- ✗ Actinium (89 protons)
- ✗ Radium (88 protons)

...

- ✗ Lead (82 protons)

Is it a heavier element with more than 92 protons?

13-minute

898 NATURE JUNE 16, 1934

Possible Production of Elements of Atomic Number Higher than 92

By PROF. E. FERMI, Royal University of Rome

Slow neutron Uranium New heavy element?

Fascists take over Italy

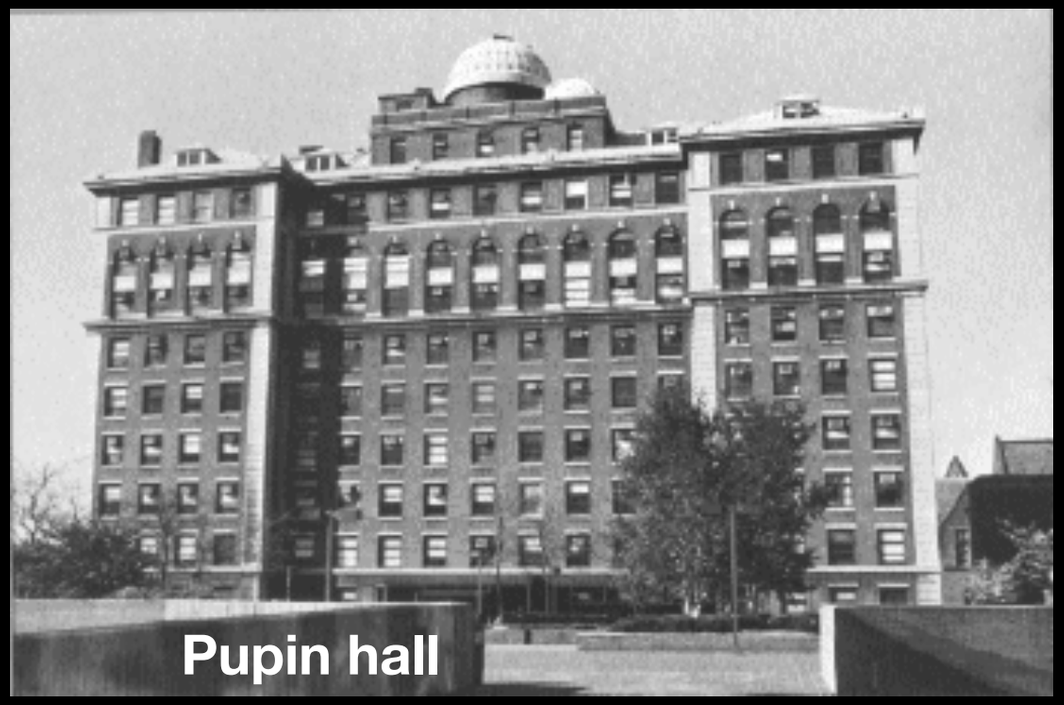
At the Nobel Prize ceremony
in Sweden *(December 1938)*

Safely arrived
in New York
(January 2, 1939)

Fermi at Columbia

The uranium nucleus has been split in Berlin!

Results made public on January 6, 1939



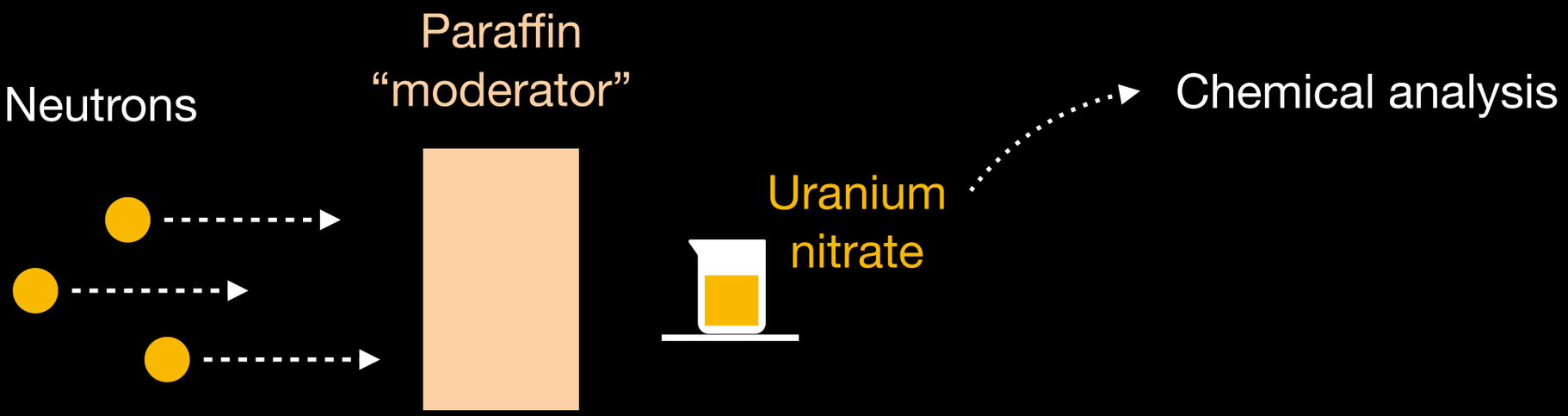
Heft 1. 6. 1. 1939] HAHN u. STRASSMANN: Über den Nachweis und das Verhalten der Erdalkalimetalle. 11

Über den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle[1].

Von O. HAHN und F. STRASSMANN, Berlin-Dahlem.

What happened in Berlin?

Virtually the same experiment as in Fermi's Via Panisperna!



„Ra I" ?	$\xrightarrow[<1\ \text{Min.}]{\beta}$	Ac I	$\xrightarrow[<30\ \text{Min.}]{\beta}$	Th ?
„Ra II"	$\xrightarrow[14 \pm 2\ \text{Min.}]{\beta}$	Ac II	$\xrightarrow[\sim 2{,}5\ \text{Std.}]{\beta}$	Th ?
„Ra III"	$\xrightarrow[86 \pm 6\ \text{Min.}]{\beta}$	Ac III	$\xrightarrow[\sim \text{mehrere Tage?}]{\beta}$	Th ?
„Ra IV"	$\xrightarrow[250\text{—}300\ \text{Std.}]{\beta}$	Ac IV	$\xrightarrow[<40\ \text{Std.}]{\beta}$	Th ?

"Radium" "Actinium" "Thorium"

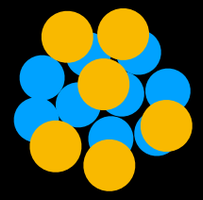
"As chemists, we would actually have to say that the new elements are not radium, but barium."

"If our 'radium isotopes' are not radium, then our 'actinium isotopes' are not actinium, but lanthanum."

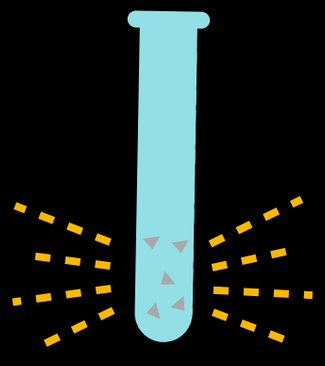
What happened in Berlin?

The nucleus is highly dynamic!

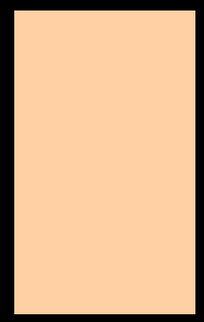
A droplet of water instead of a bowling ball.



Barium
(56 protons)



Paraffin
“moderator”



Uranium
nitrate

13-minute
half-life

Chemical separation:

- ✗ Uranium (92 protons)
- ✗ Palladium (91 protons)
- ✗ Thorium (90 protons)
- ✗ Actinium (89 protons)
- ✗ Radium (88 protons)

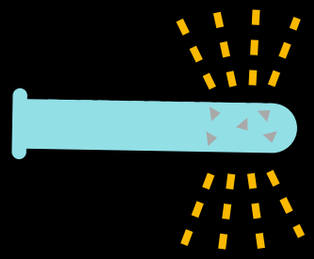
…

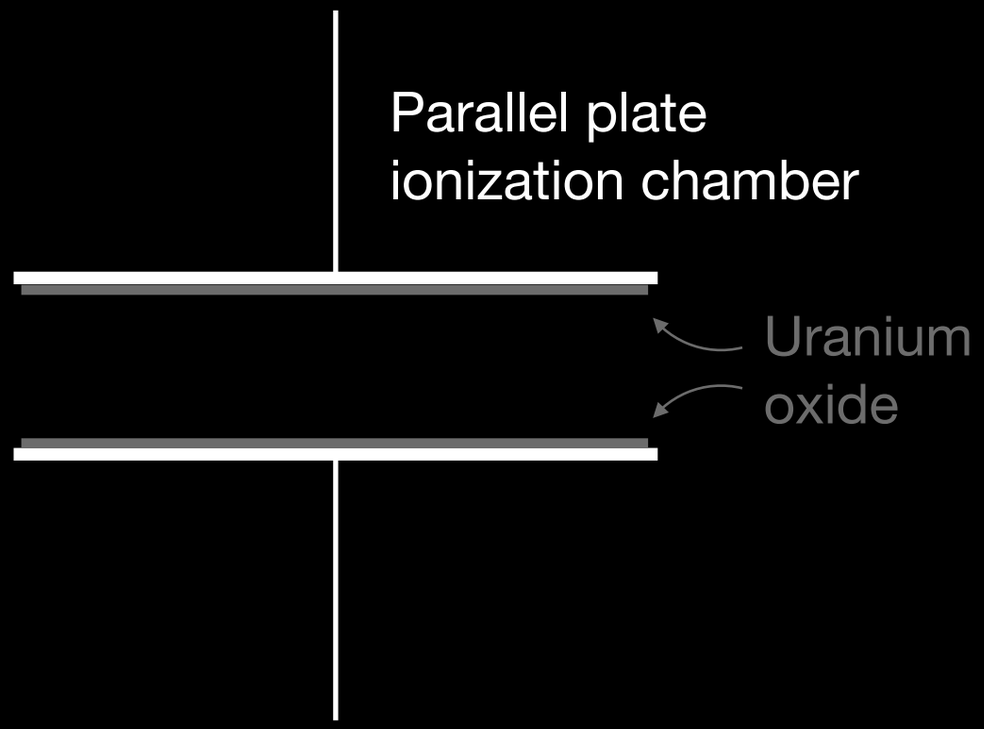
- ✗ Lead (82 protons)

Enrico Fermi, Via Panisperna *(1934)*

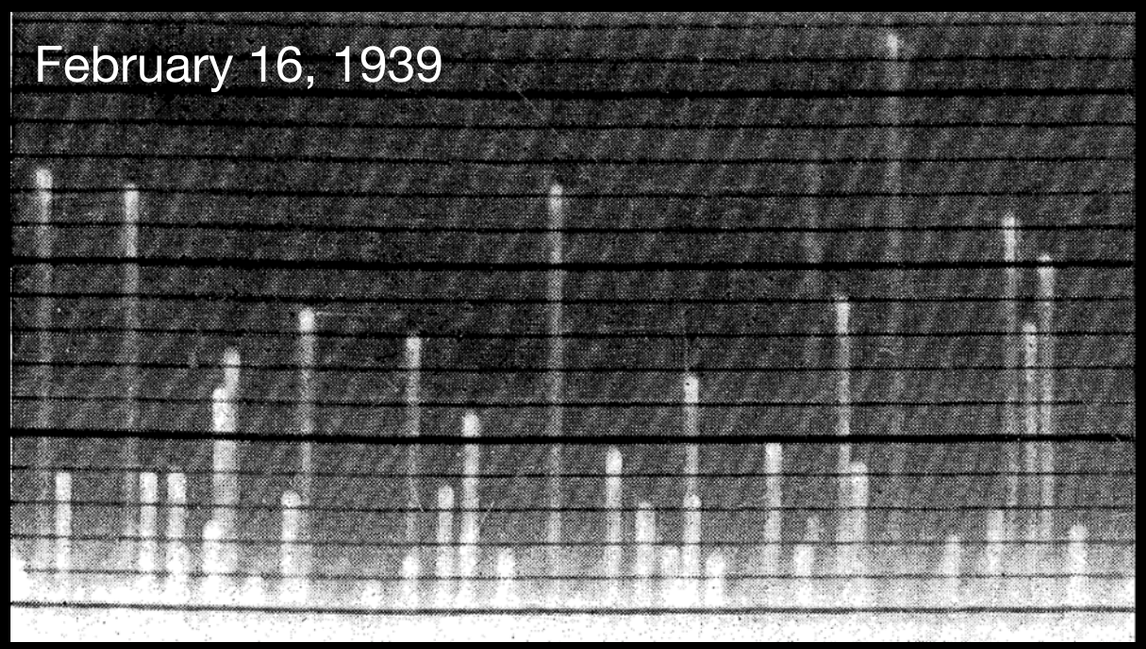
Fermi's reaction

"I want to see this for myself!"





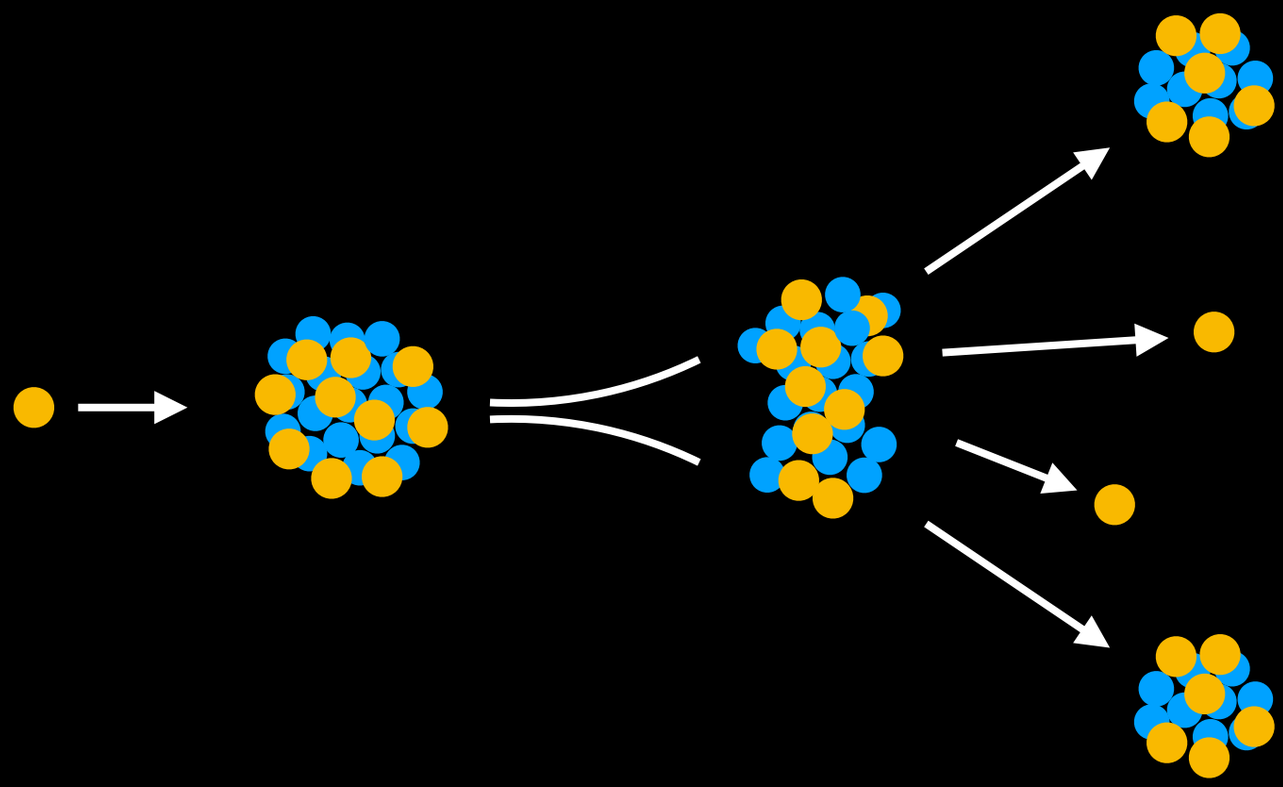
Herbert Anderson



"A large number of small pulses from the α-particles of uranium were observed."

"When exposed to the bombardment of neutrons very large pulses occurred in addition."

A chain reaction?



Additional neutrons?

If so, *how many*?

Less than one

(on average)

Reaction will eventually stop

More than one

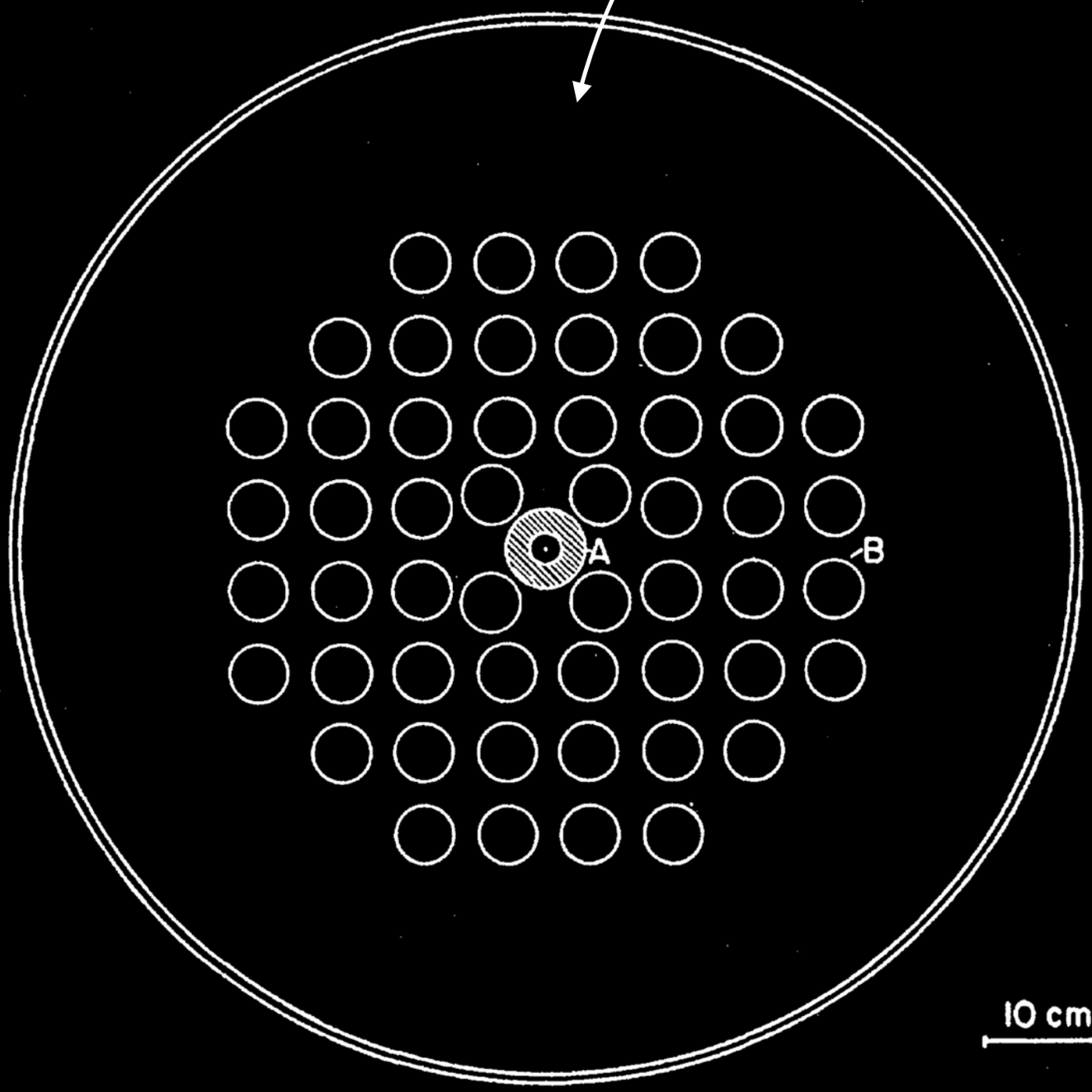
(on average)

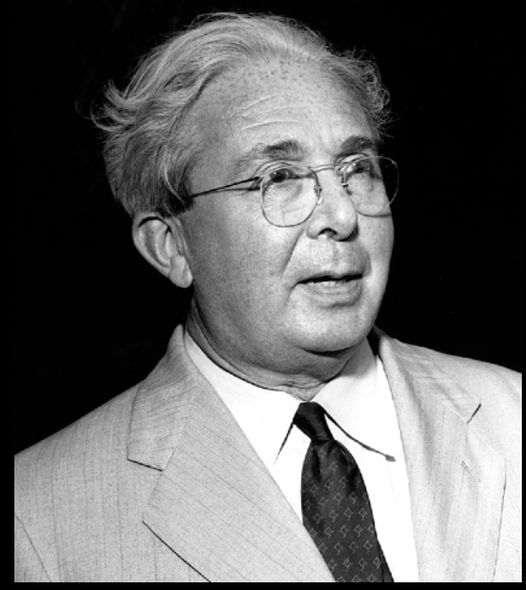
Reaction will continue indefinitely

How many neutrons?

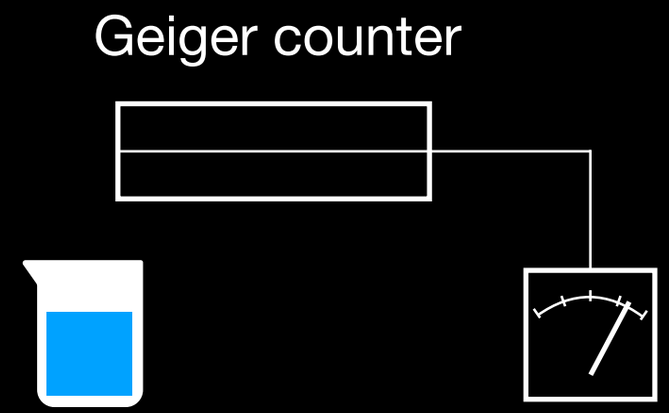
Water + Manganese salt

(Activated by neutrons)





Leo Szilard

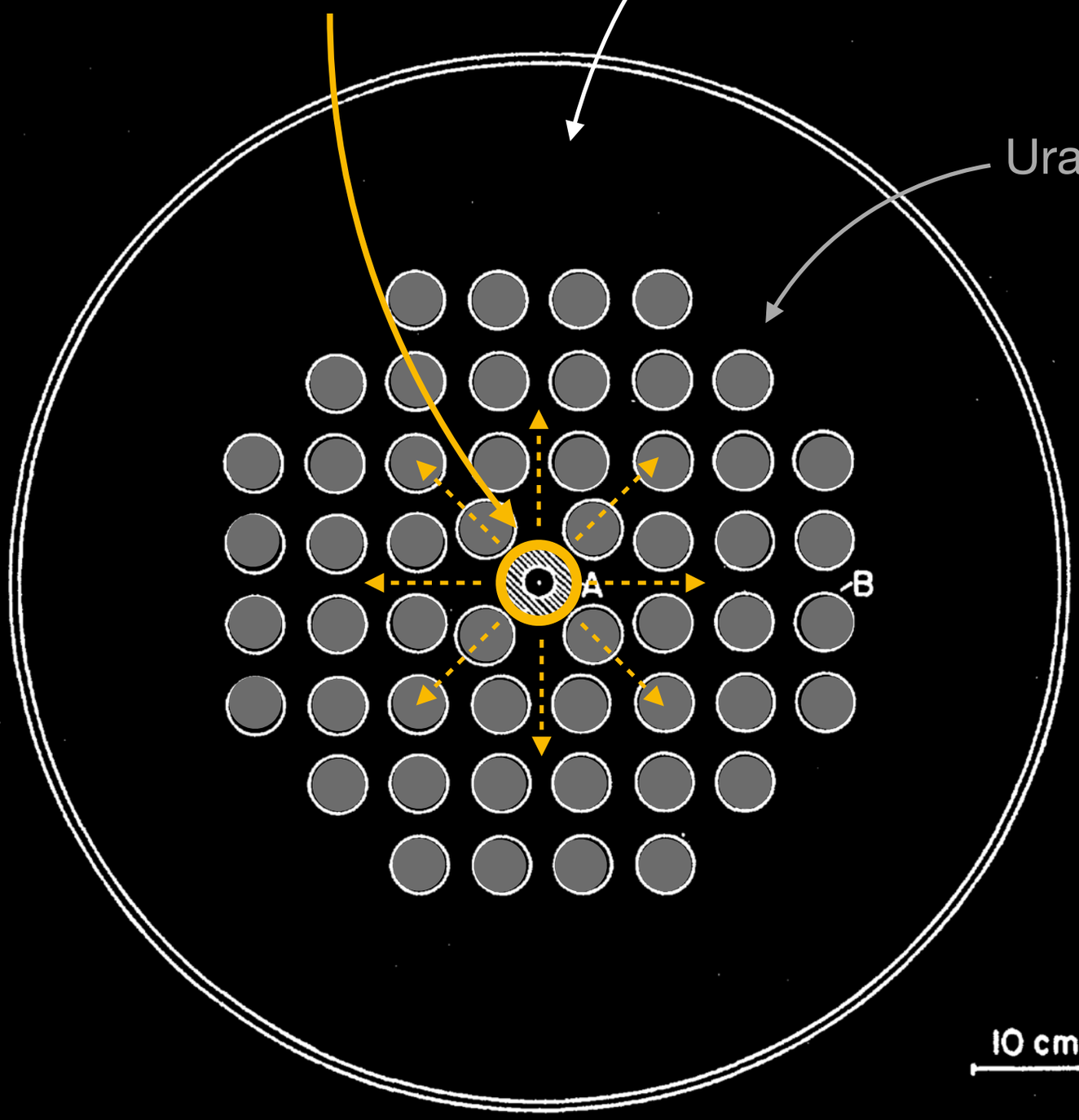


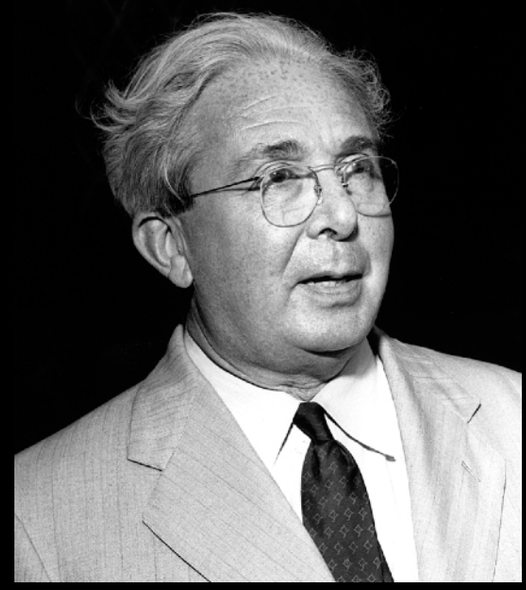
Radioactivity of water + salt

↕

Number of neutrons

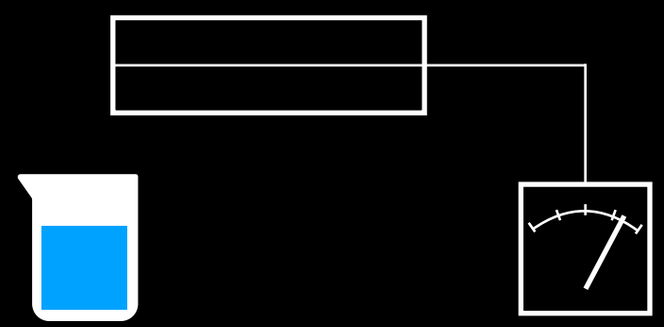
How many neutrons?





Leo Szilard

Geiger counter

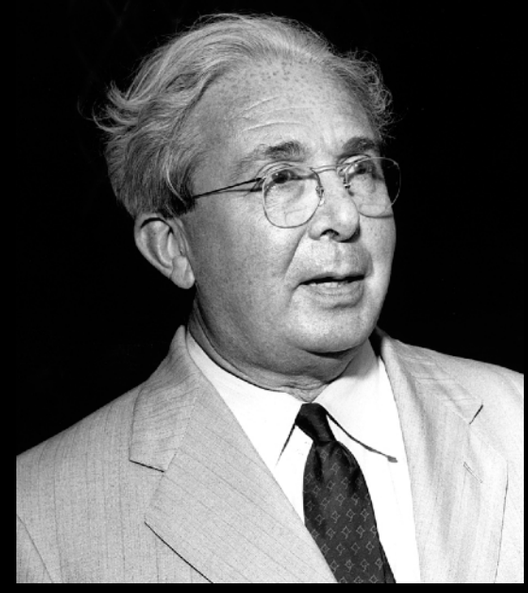


Radioactivity of water + salt

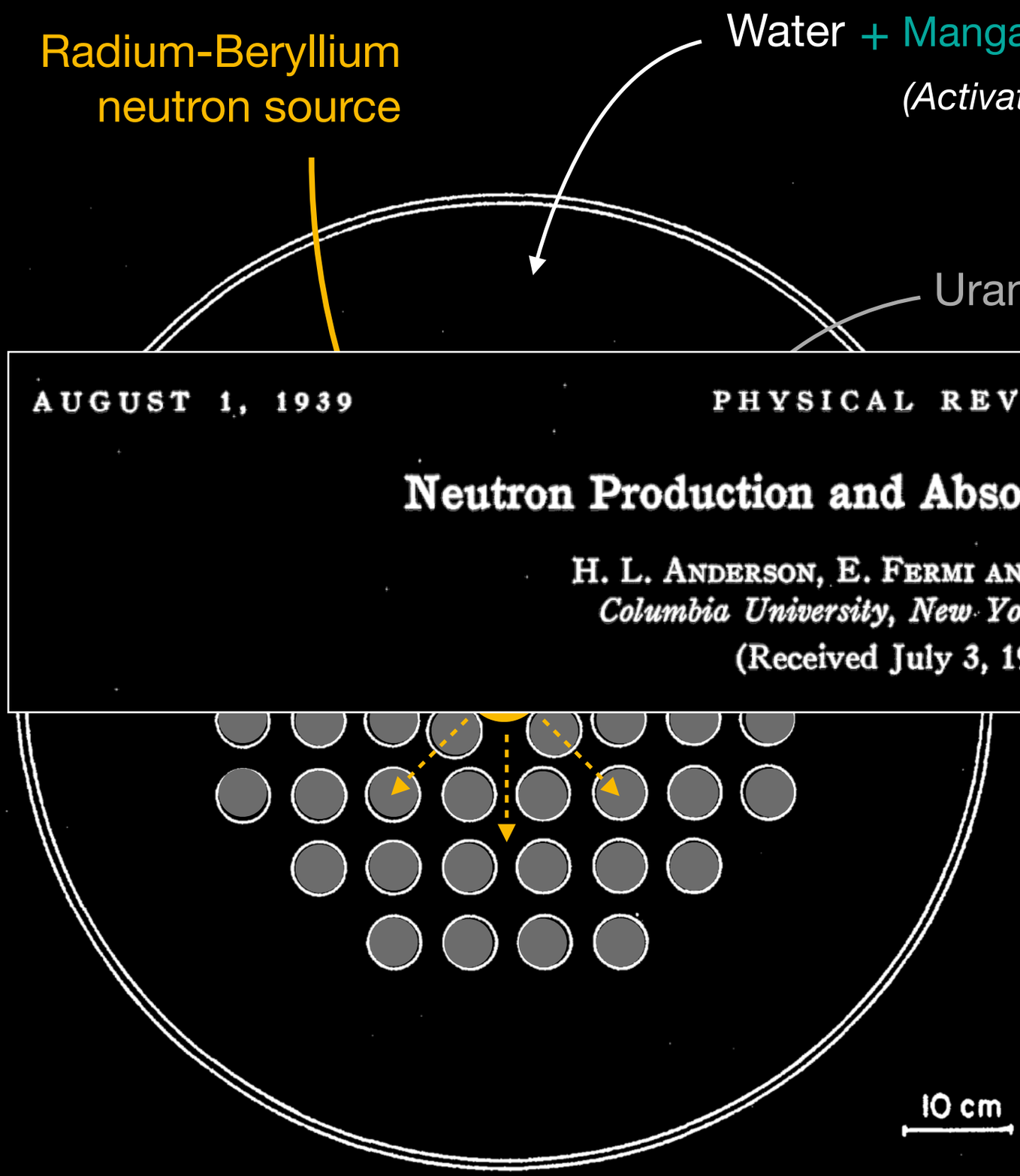
↕

Number of neutrons

How many neutrons?



Leo Szilard



AUGUST 1, 1939 PHYSICAL REVIEW VOLUME 56

Neutron Production and Absorption in Uranium*

H. L. Anderson, E. Fermi and Leo Szilard
Columbia University, New York, New York

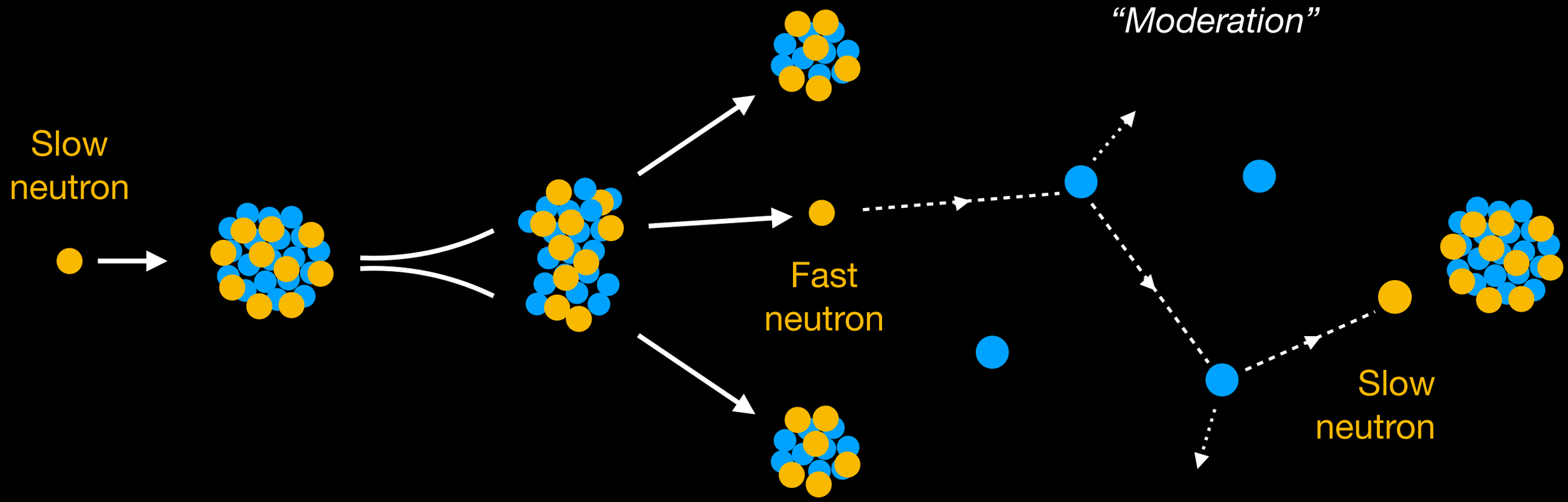
(Received July 3, 1939)

"This corresponds to an average emission of about 1.2 neutrons per thermal neutron absorbed by uranium."

A practical chain reaction?

A self-sustaining chain reaction is possible in principle …

… how to make it work in practice?

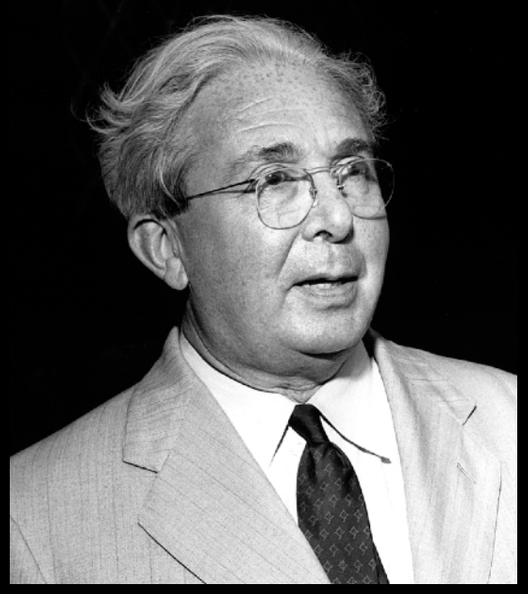


“1.5 neutrons per fission”

→ quite tight!

Need to slow down neutrons without losing them!

The Hungarians visit Einstein



Leo Szilard

Edward Teller

Eugene Wigner

The Hungarians visit Einstein

Le

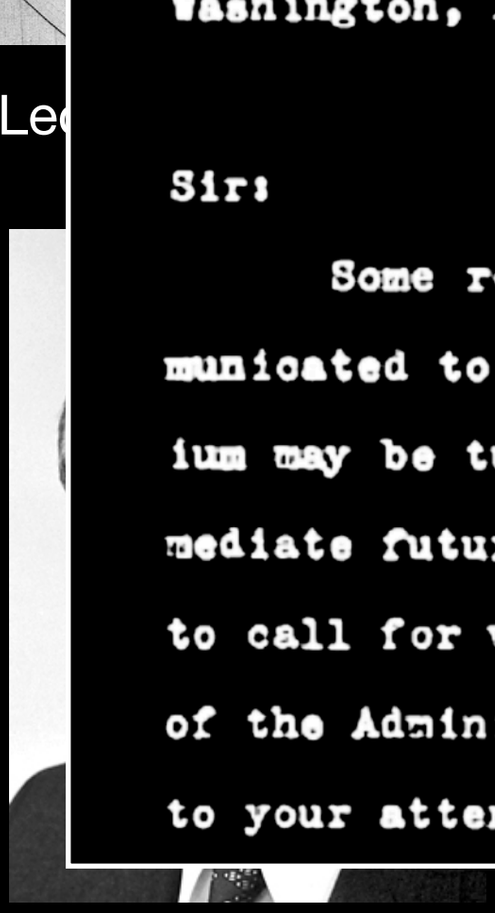
Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

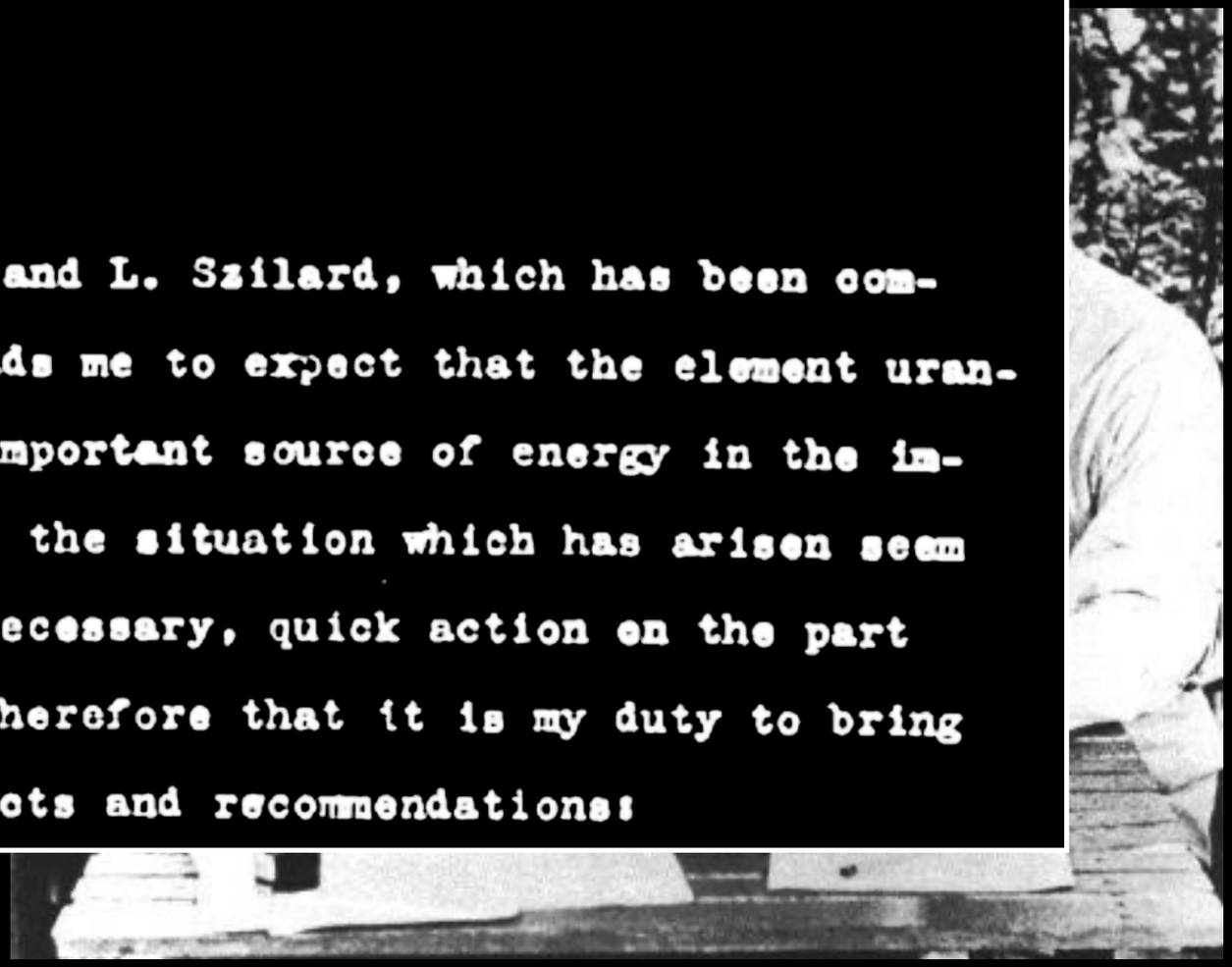
F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

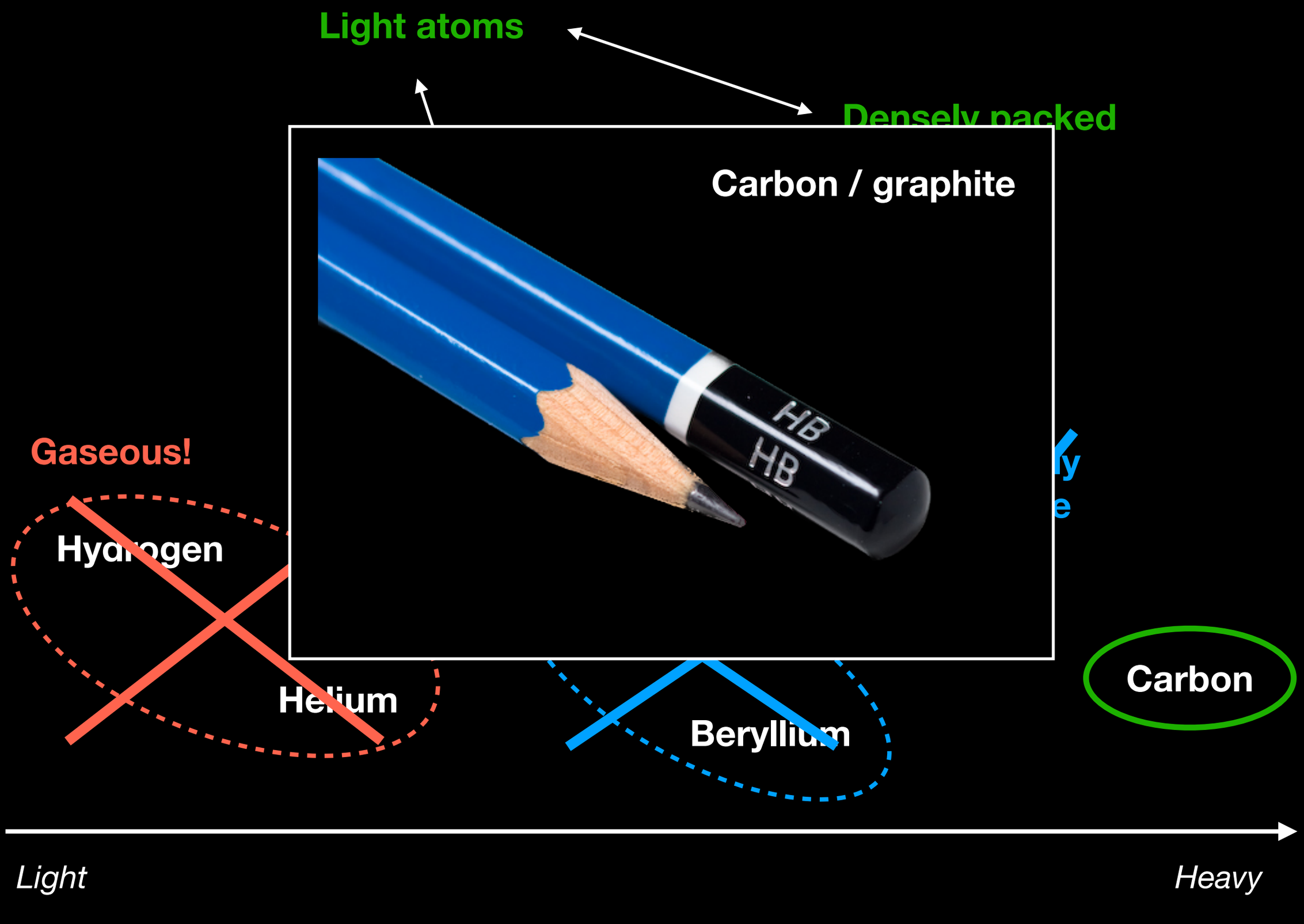
Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:



Eugene Wigner

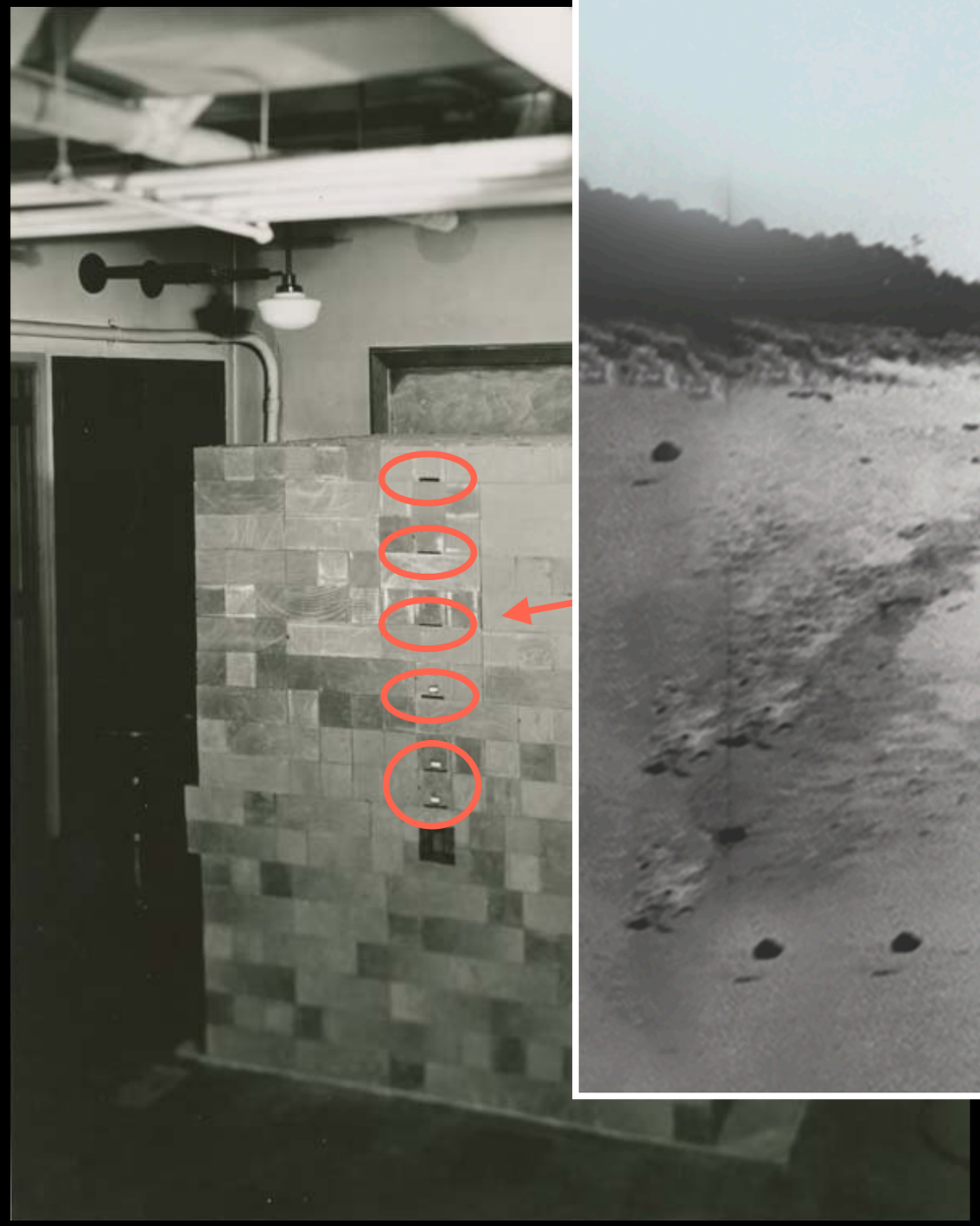


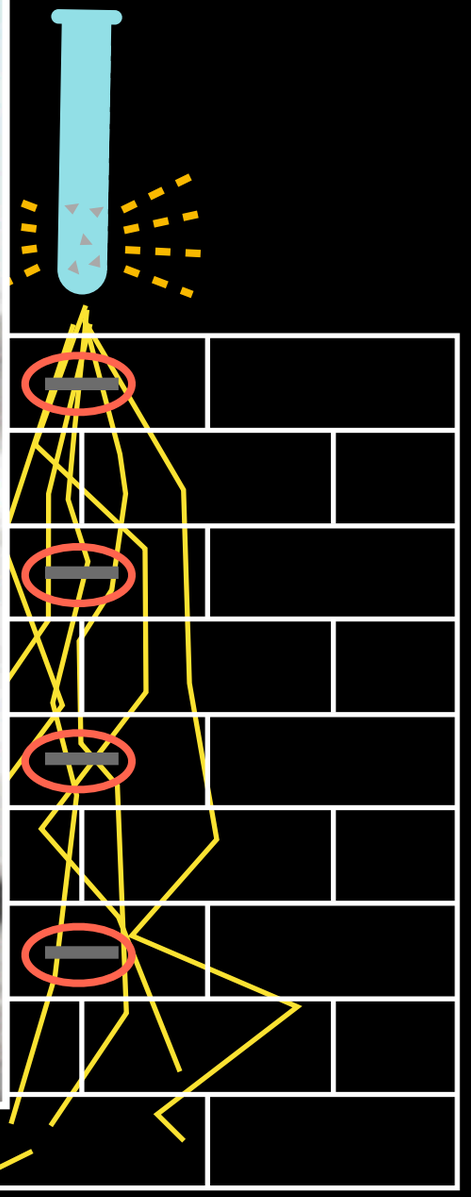
Which moderator to use?



Measuring neutron diffusion

Spring 1940





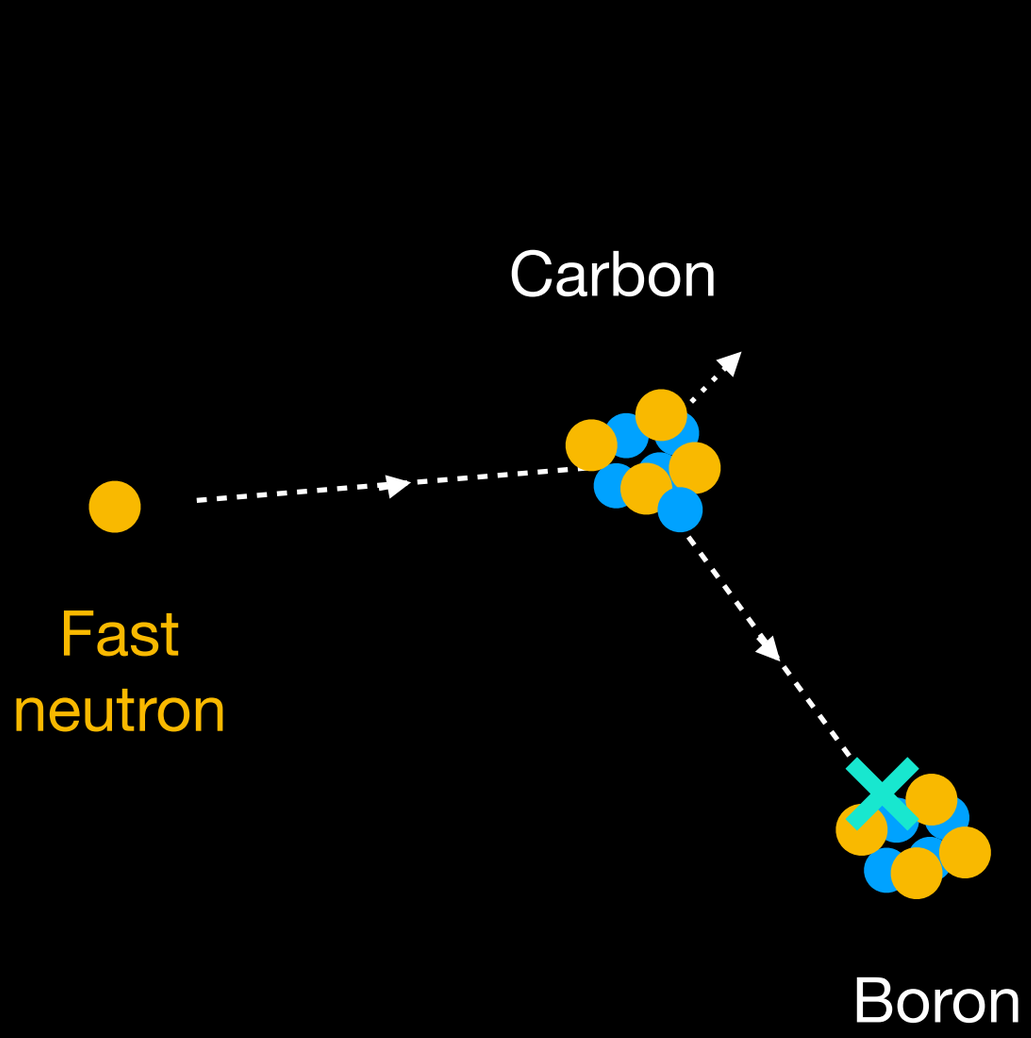
Test pile at Columbia

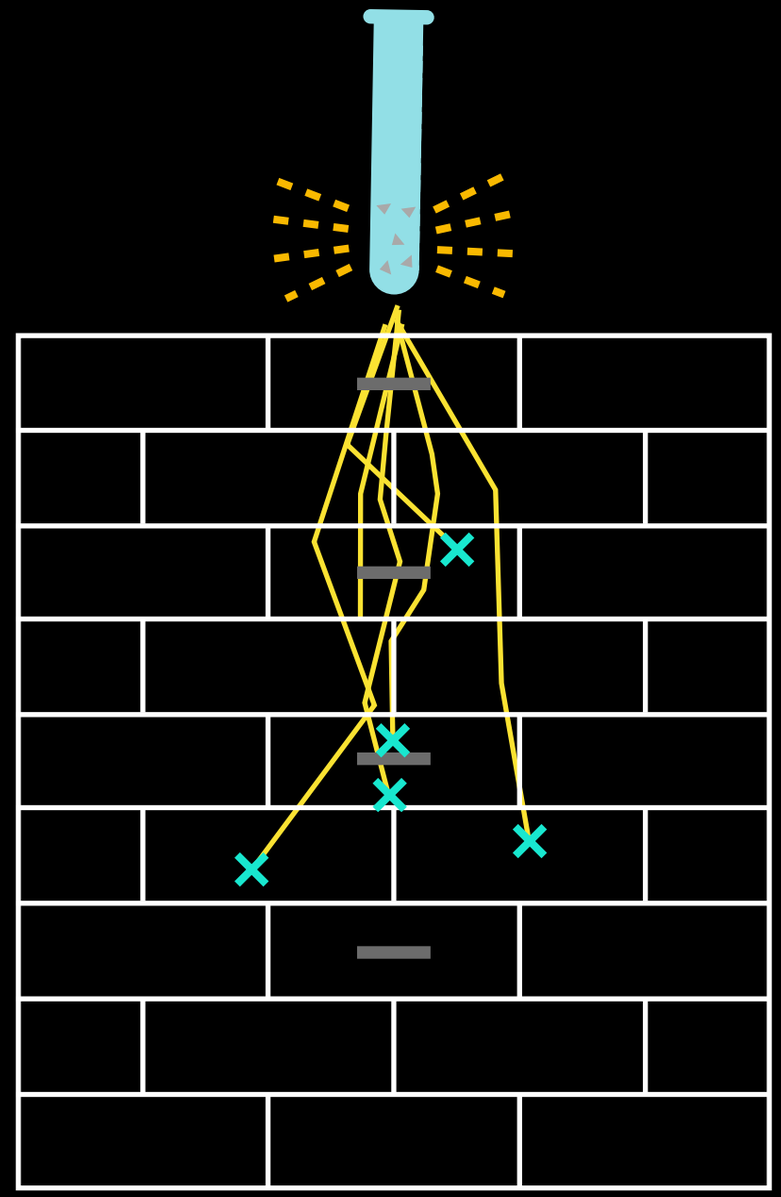
Measuring neutron diffusion

Spring 1940

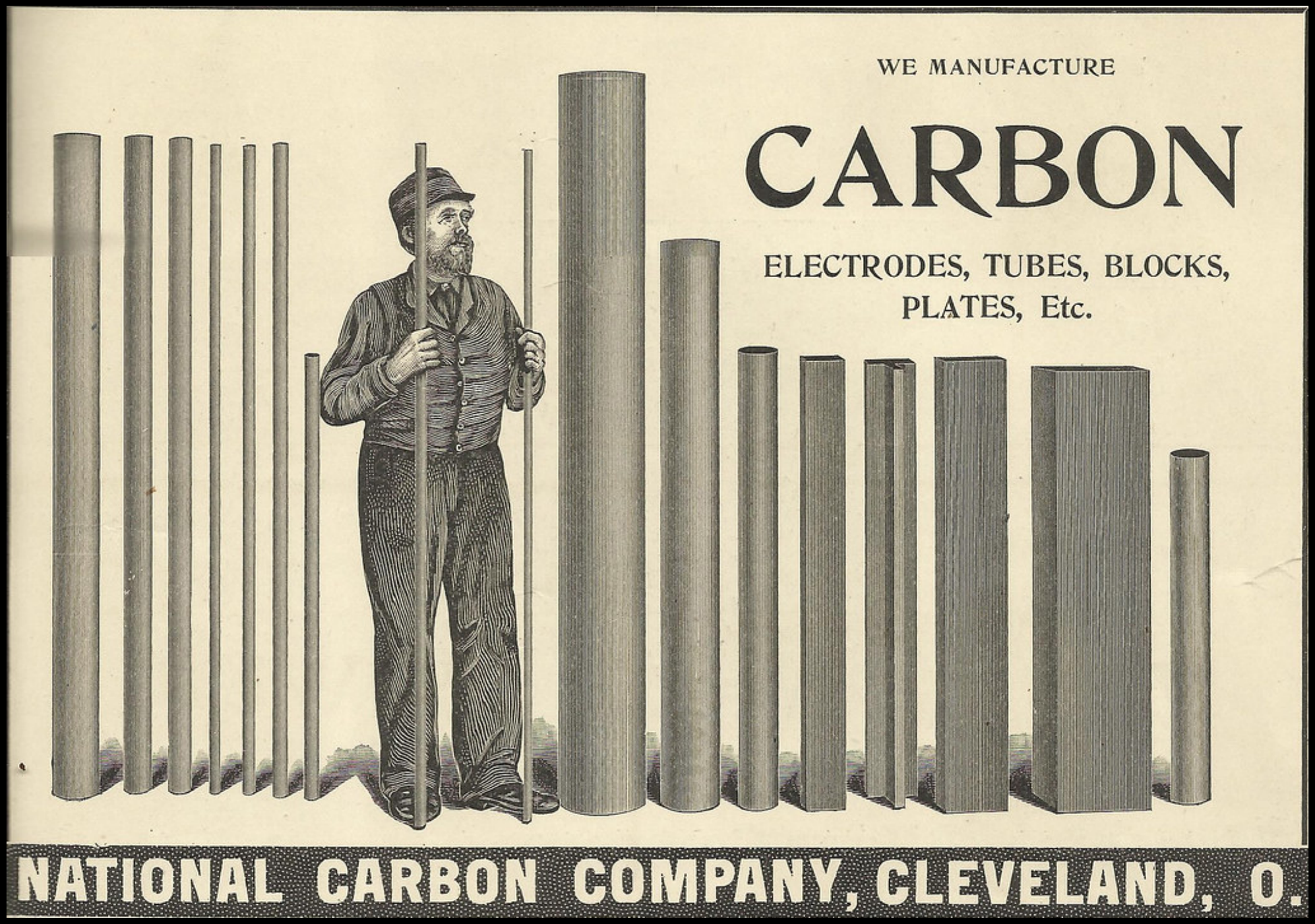
Too many neurons are absorbed!

→ *Boron impurities in graphite!*

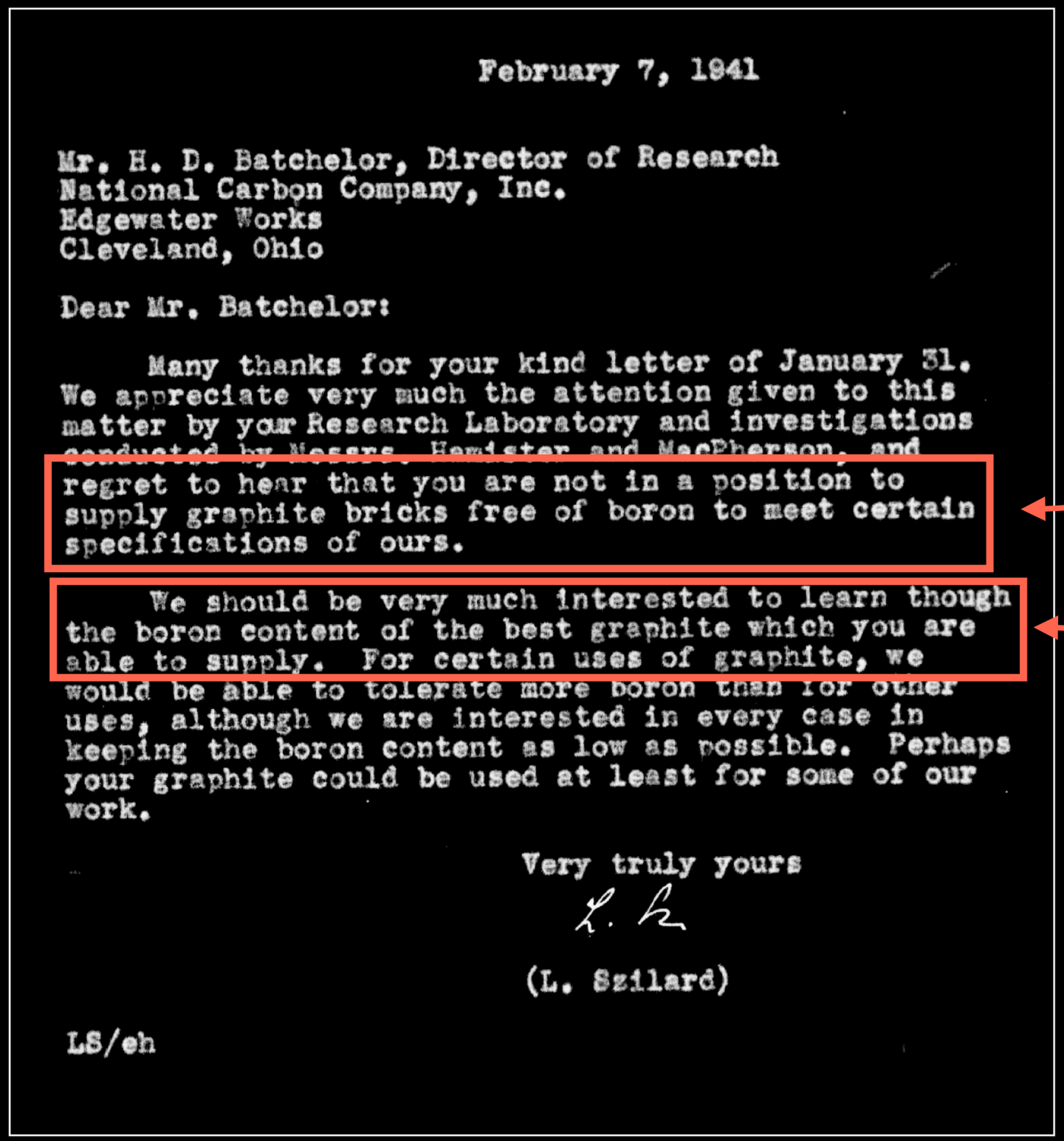




Szilard scrounges graphite



Szilard scrounges graphite



February 7, 1941

Mr. H. D. Batchelor, Director of Research
National Carbon Company, Inc.
Edgewater Works
Cleveland, Ohio

Dear Mr. Batchelor:

Many thanks for your kind letter of January 31. We appreciate very much the attention given to this matter by your Research Laboratory and investigations conducted by Messrs. Hemister and MacPherson, and regret to hear that you are not in a position to supply graphite bricks free of boron to meet certain specifications of ours.

We should be very much interested to learn though the boron content of the best graphite which you are able to supply. For certain uses of graphite, we would be able to tolerate more boron than for other uses, although we are interested in every case in keeping the boron content as low as possible. Perhaps your graphite could be used at least for some of our work.

Very truly yours

L. Sz

(L. Szilard)

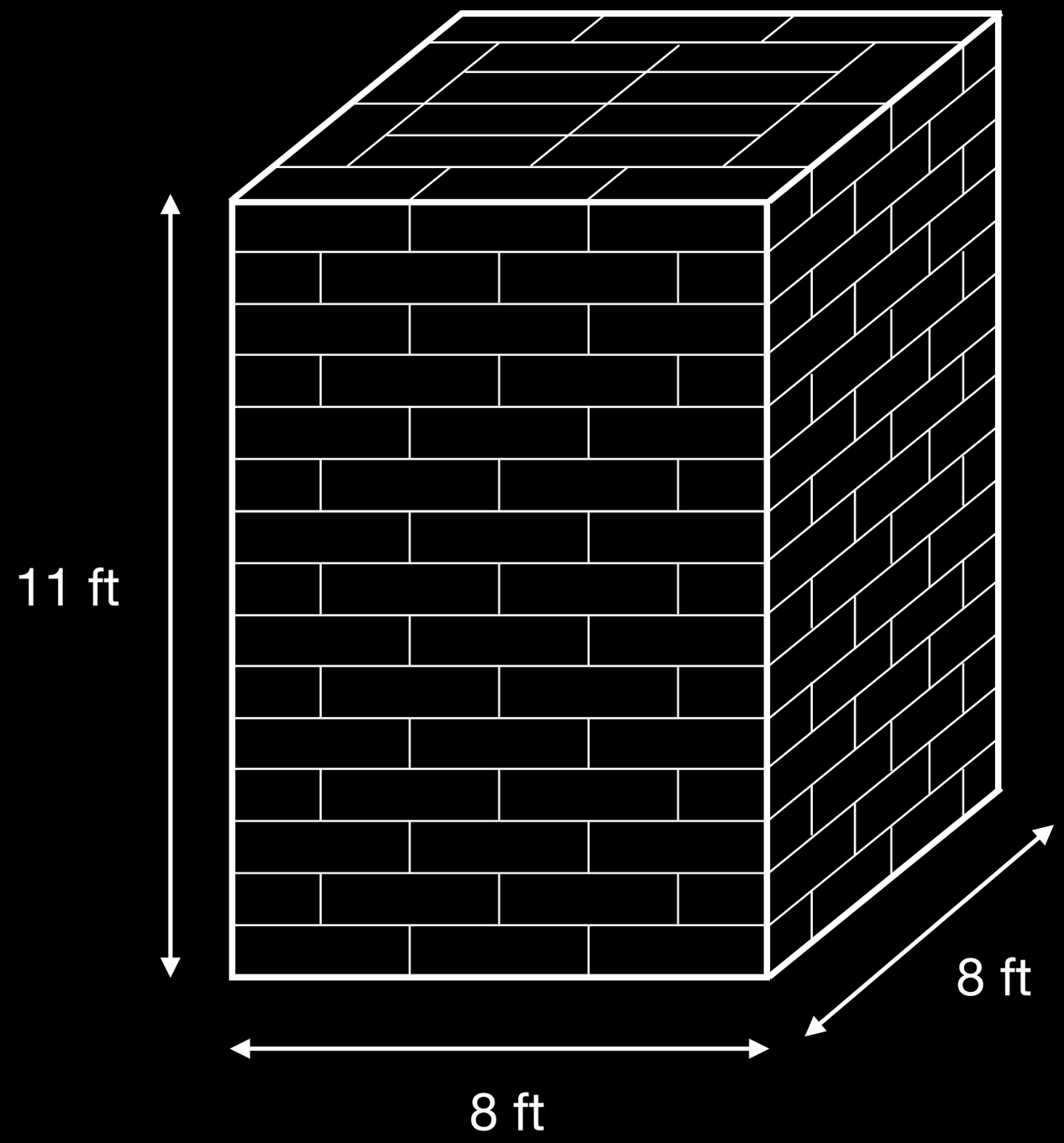
LS/eh

"[We] regret to hear that you are not in a position to supply graphite bricks free of boron to meet certain specifications of ours."

"We should be very much interested to learn the boron content of the best graphite which you are able to supply …"

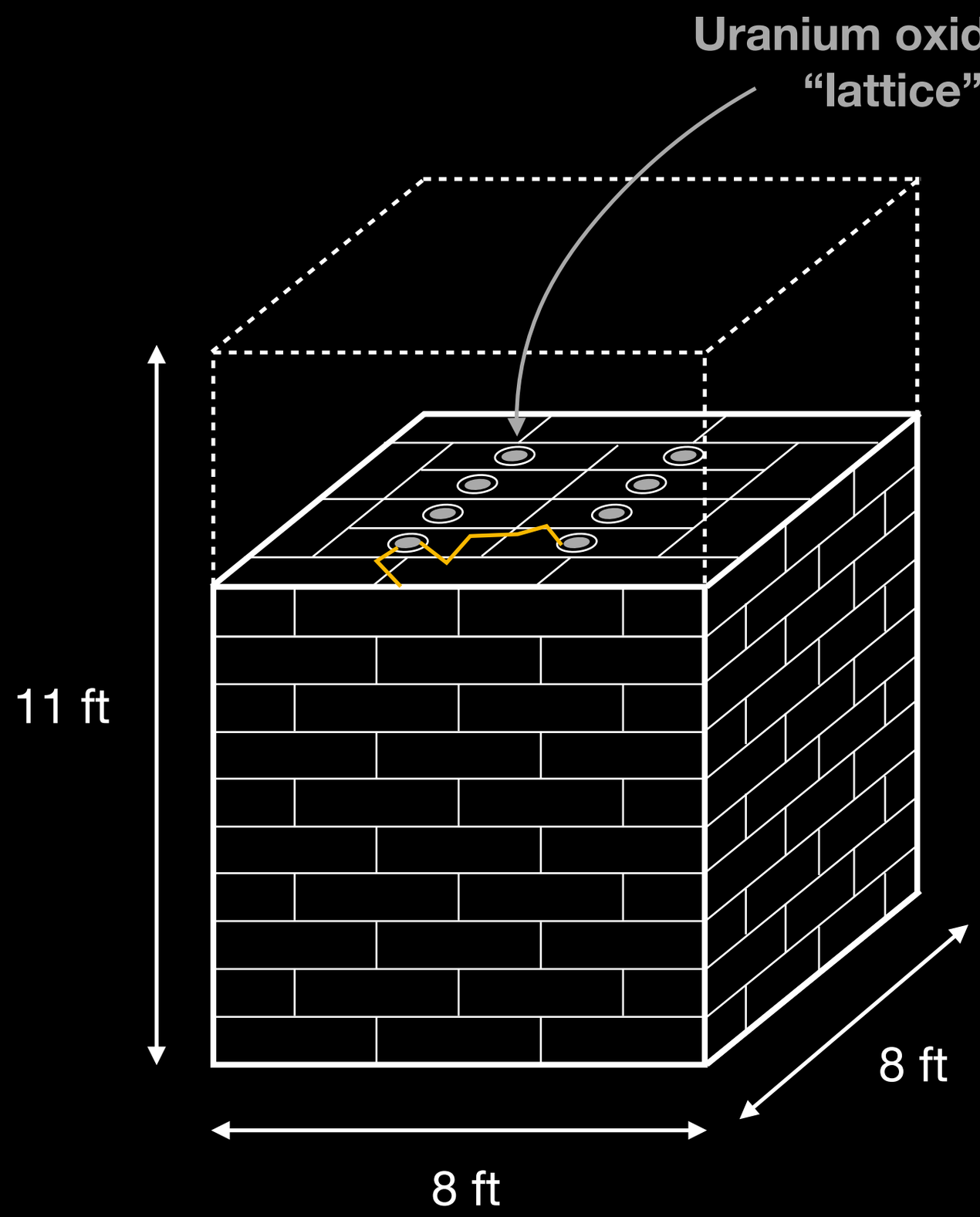
Test piles at Columbia

September 1941



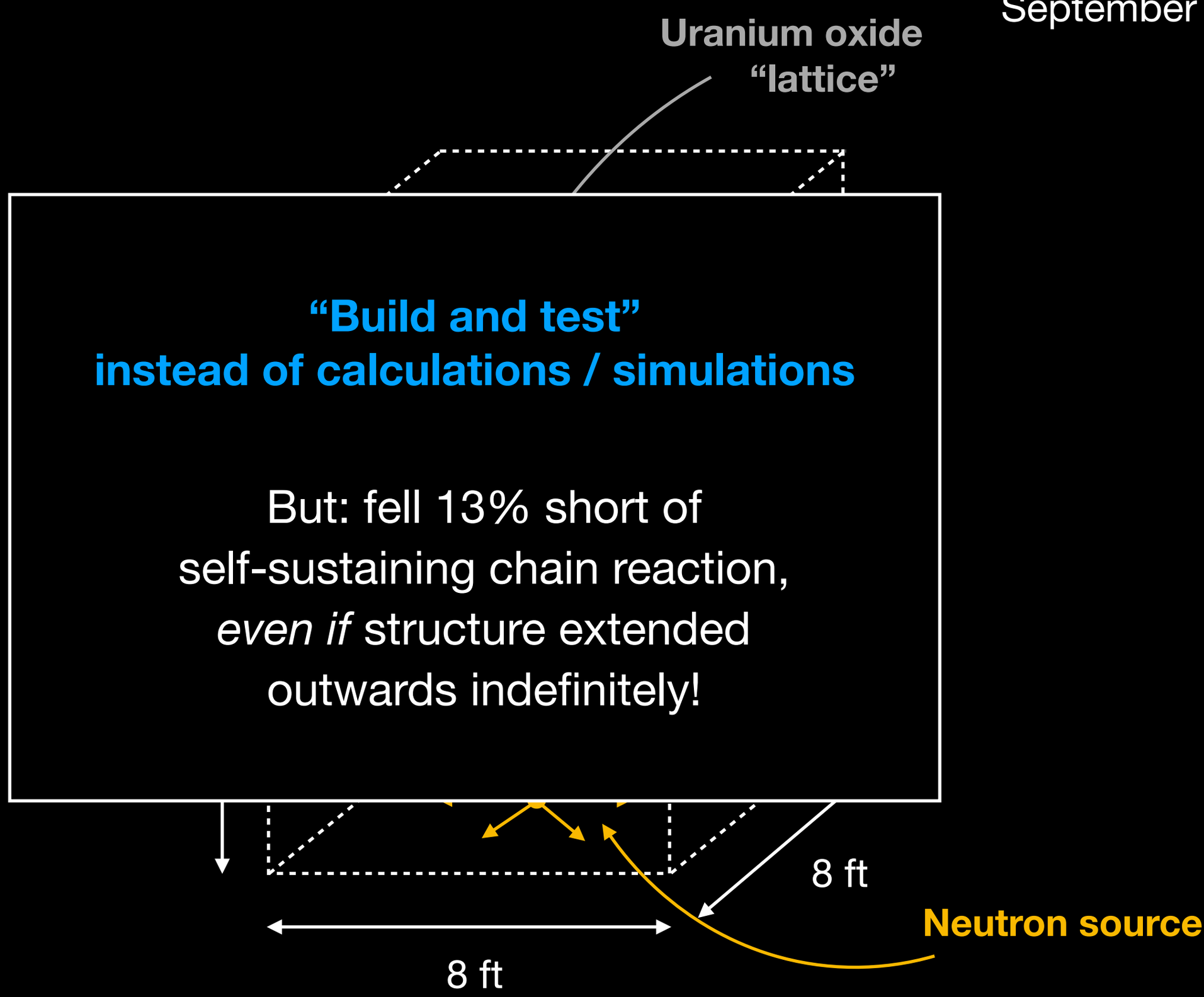
Test piles at Columbia

September 1941



Test piles at Columbia

September 1941



A sense of urgency …

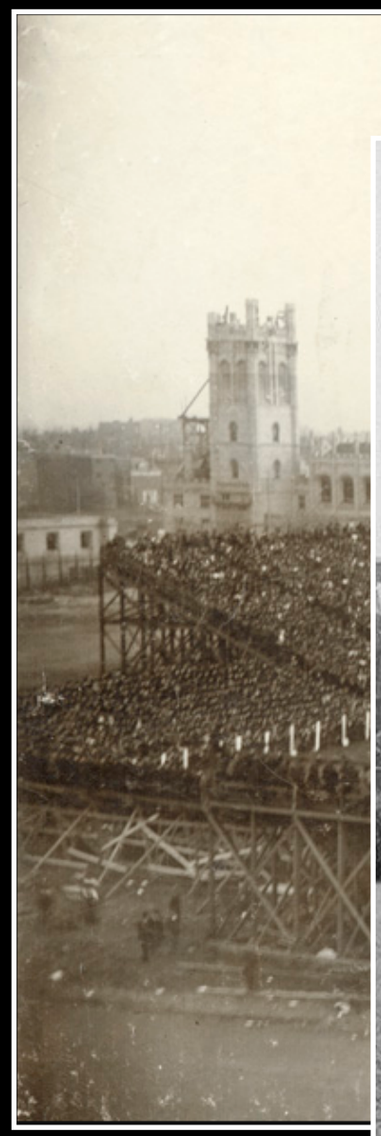
December 1941

… and a move to Chicago

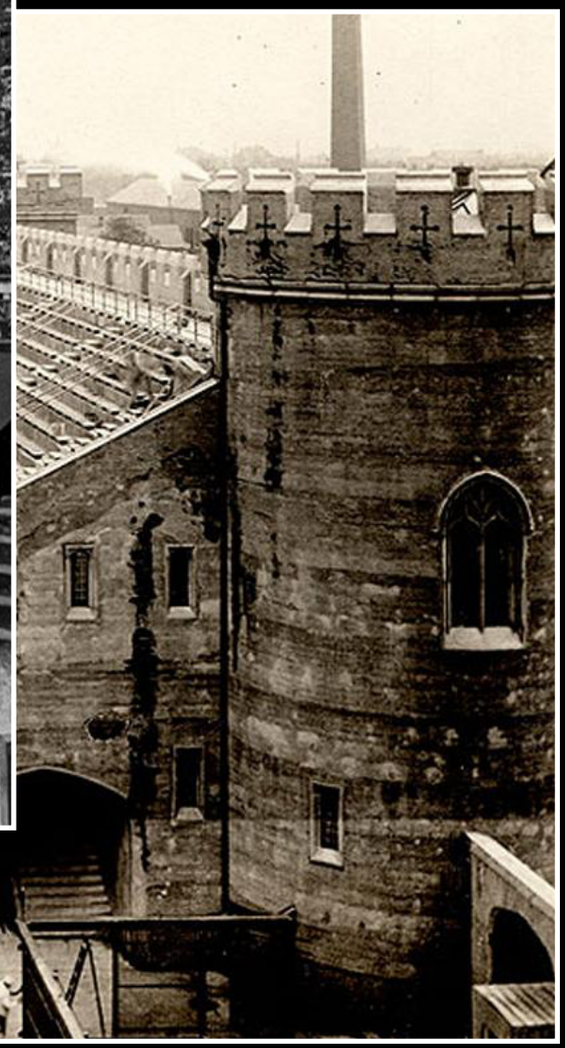
The metallurgical laboratory

Stagg Field

President Robert Hutchins on football (1939):
an “infernal nuisance” distracting from academics

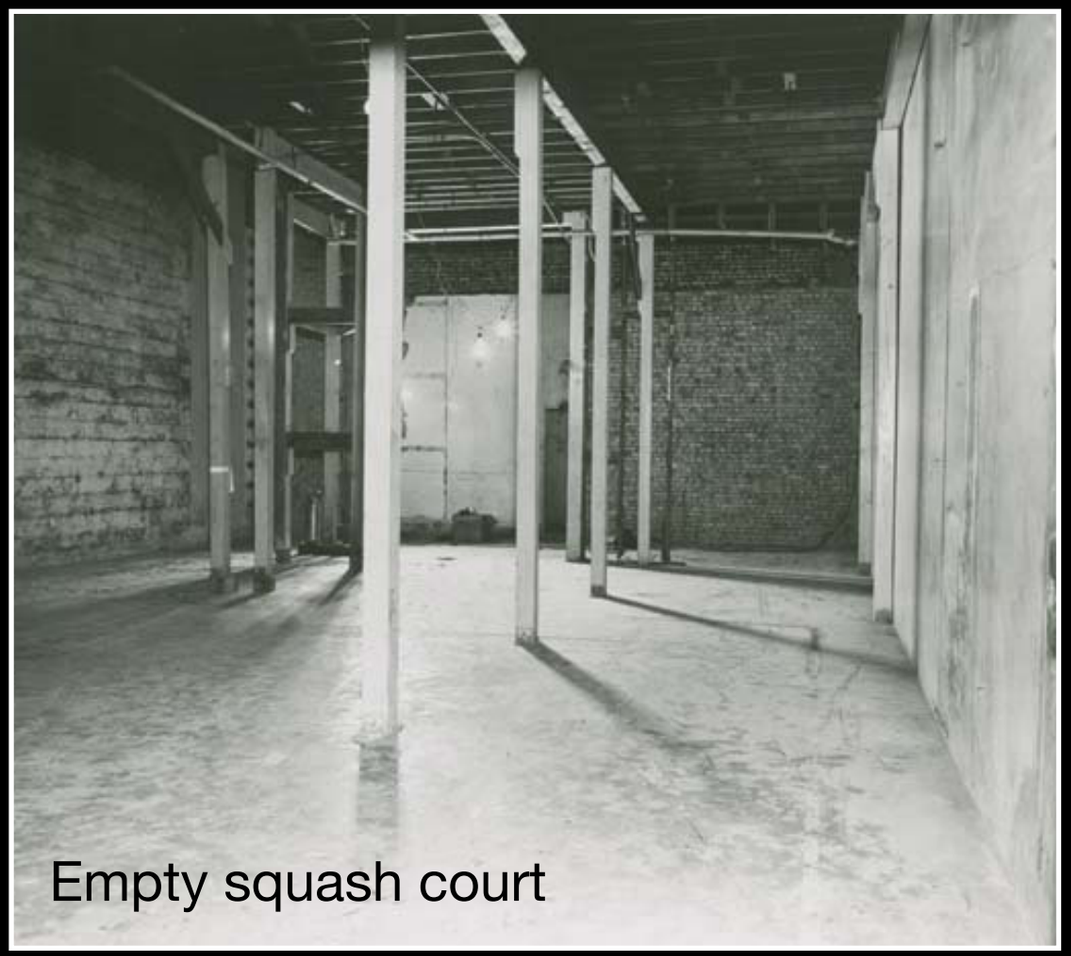


Marshall field, ca. 1900

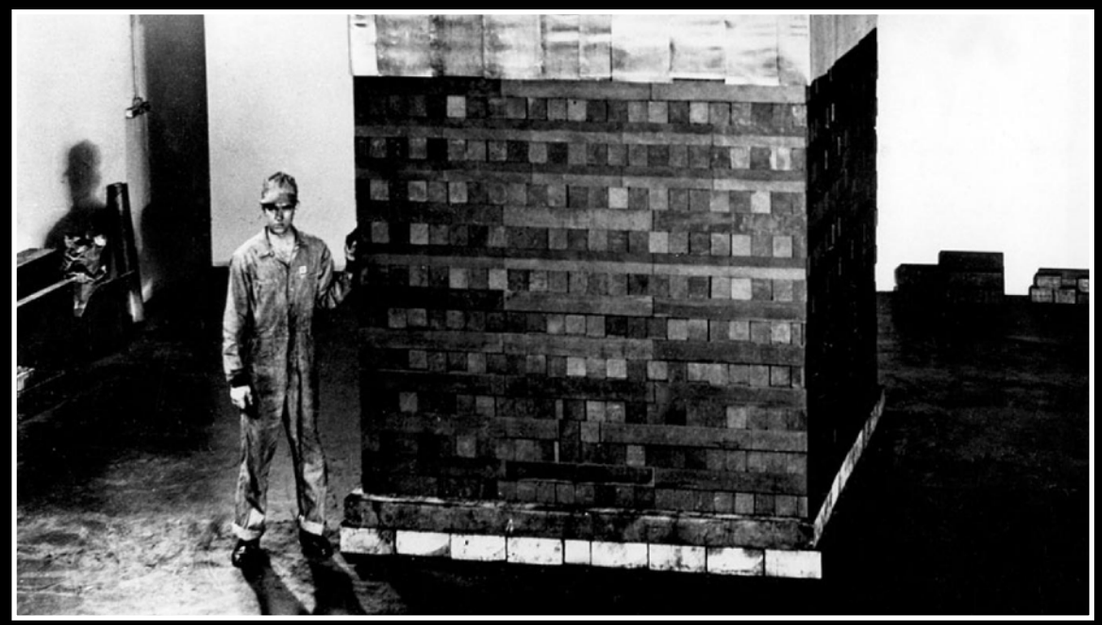


Stagg field west stand, 1930s

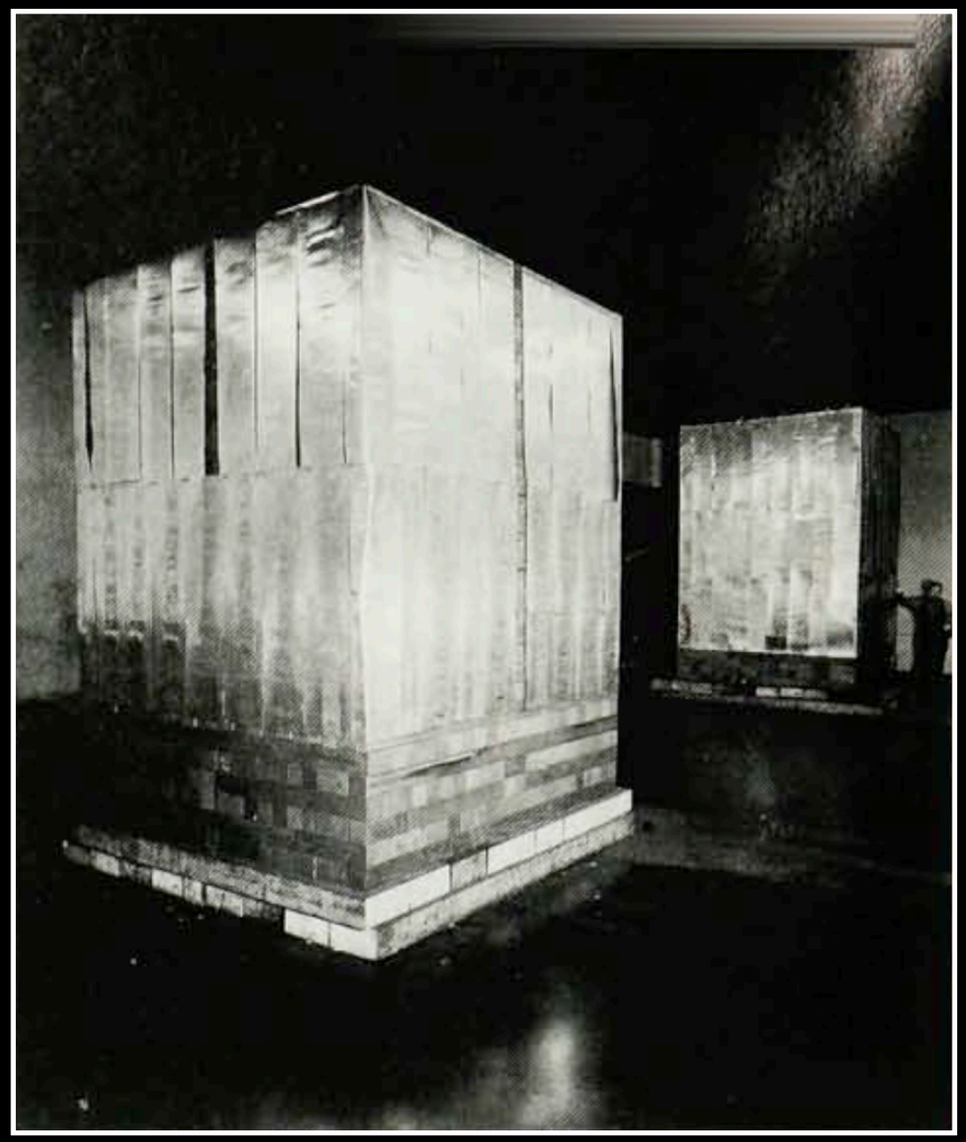
First test piles at Stagg Field



Empty squash court

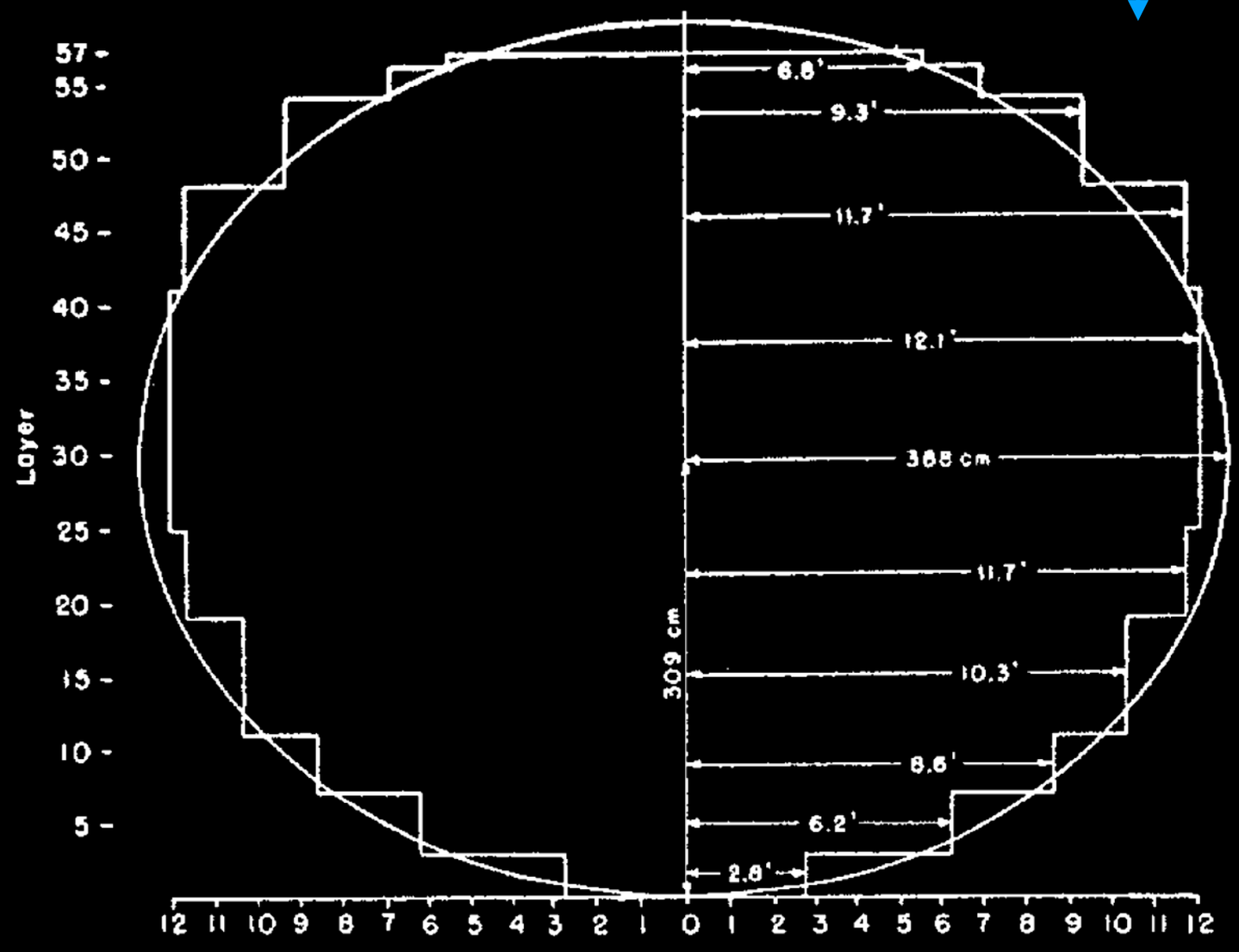


Improving the Pile



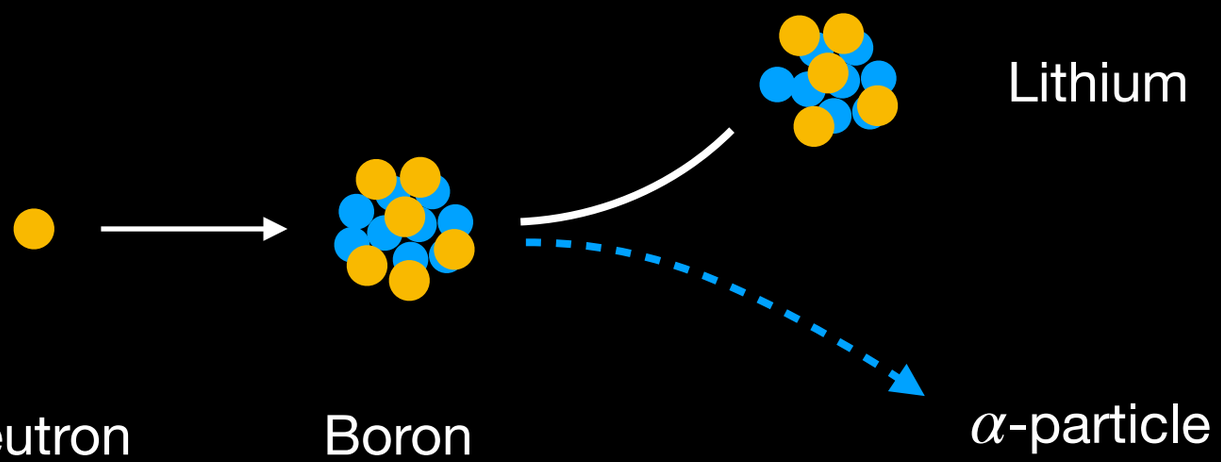
← **Columbia / early Chicago piles:**
Rectangular → easy to build, but large neutron losses

Loss-minimizing shape: ↓
As close to a sphere as possible



Improving the pile

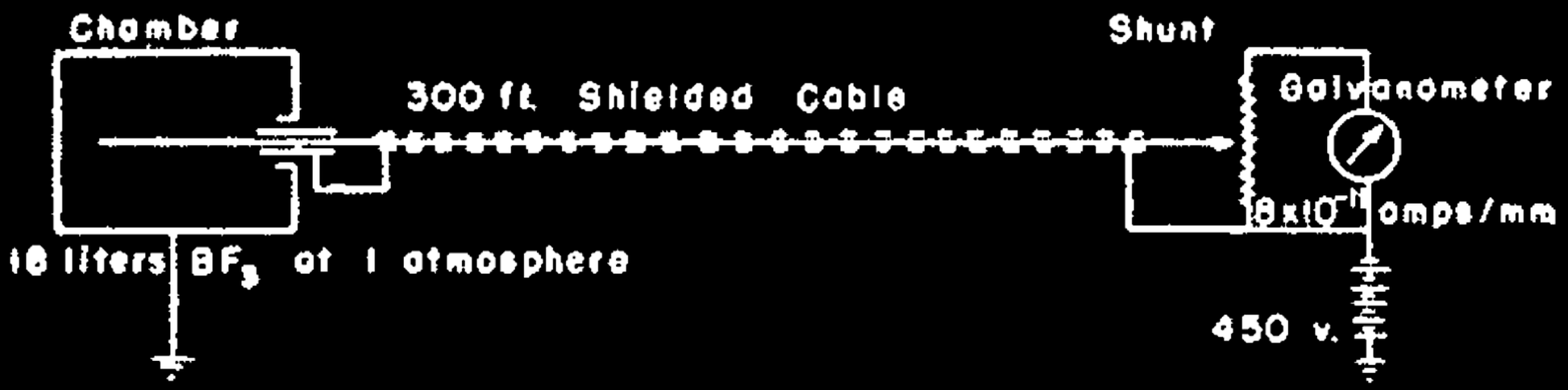
Boron-trifluoride (BF_3) counters …



… turn a nuisance into a virtue

Leona Woods

Detection chamber inside the pile



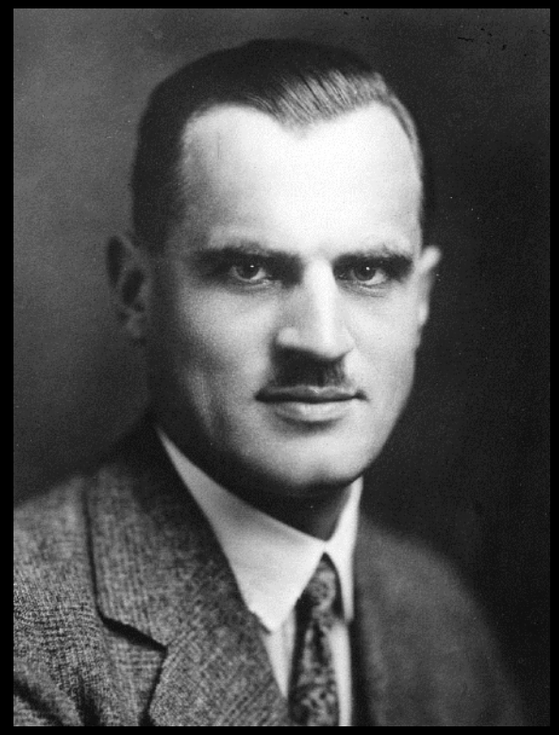
Readout instrument

The site of the first pile

Argonne Forest
Preserve

“Site A”
(Today: Close to
Argonne National Lab)

The site of the first pile



The workers at Argonne were on strike!

“Should we build the pile at Stagg Field?”

Arthur Compton:

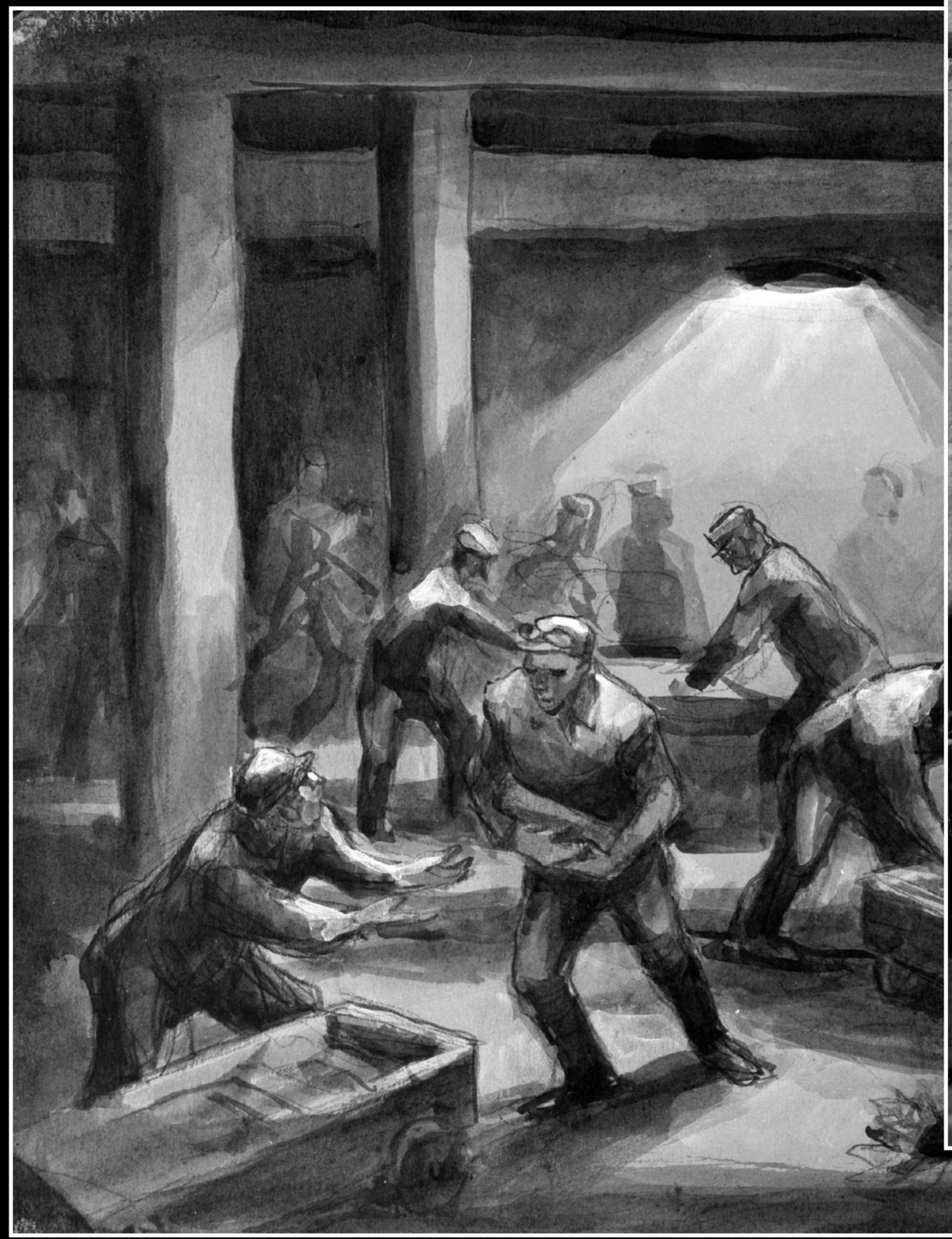
“As a responsible officer of the University, according to every rule of organizational protocol, I should have taken the matter to my superior.

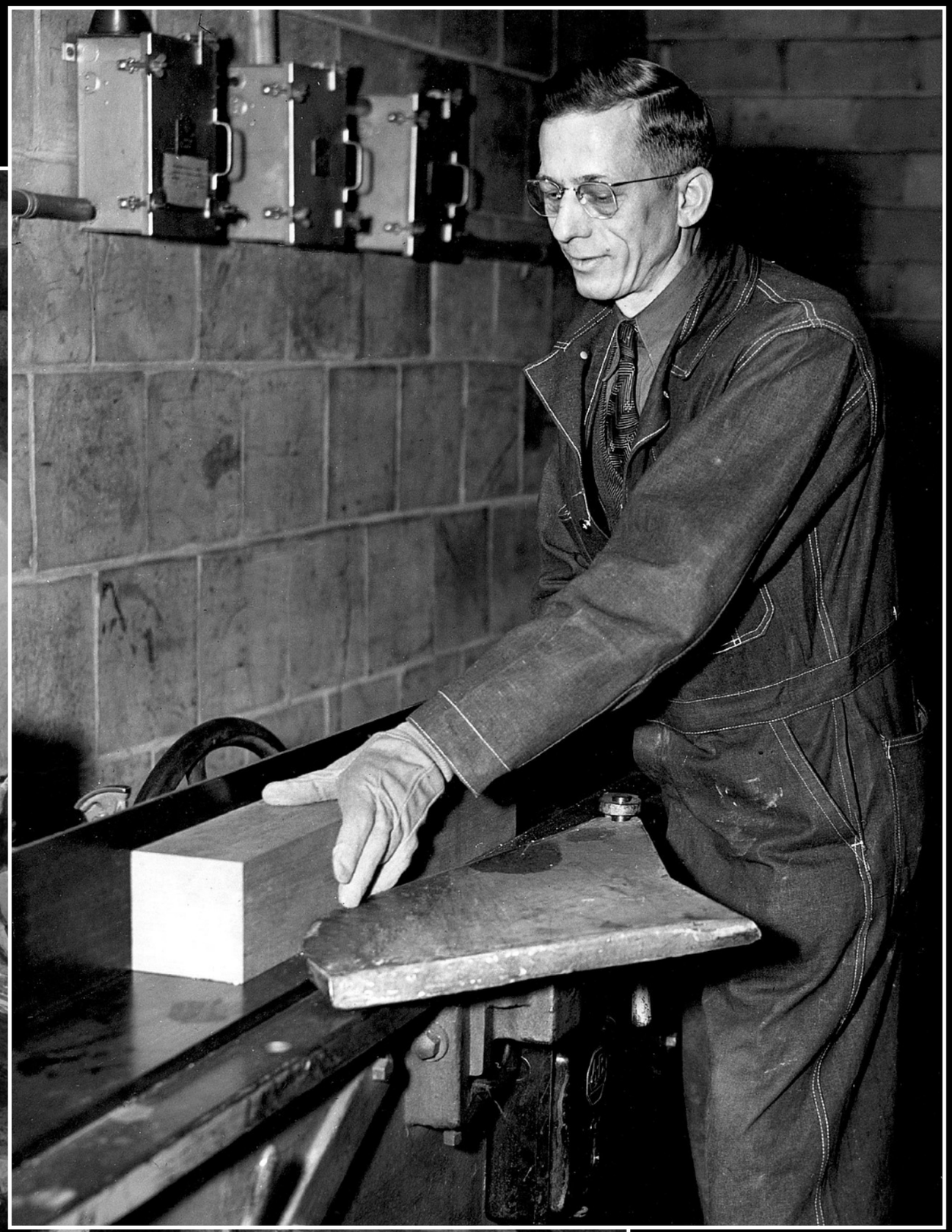
But that would have been unfair.

Based on considerations of the University’s welfare, the only answer he could have given would have been—no.

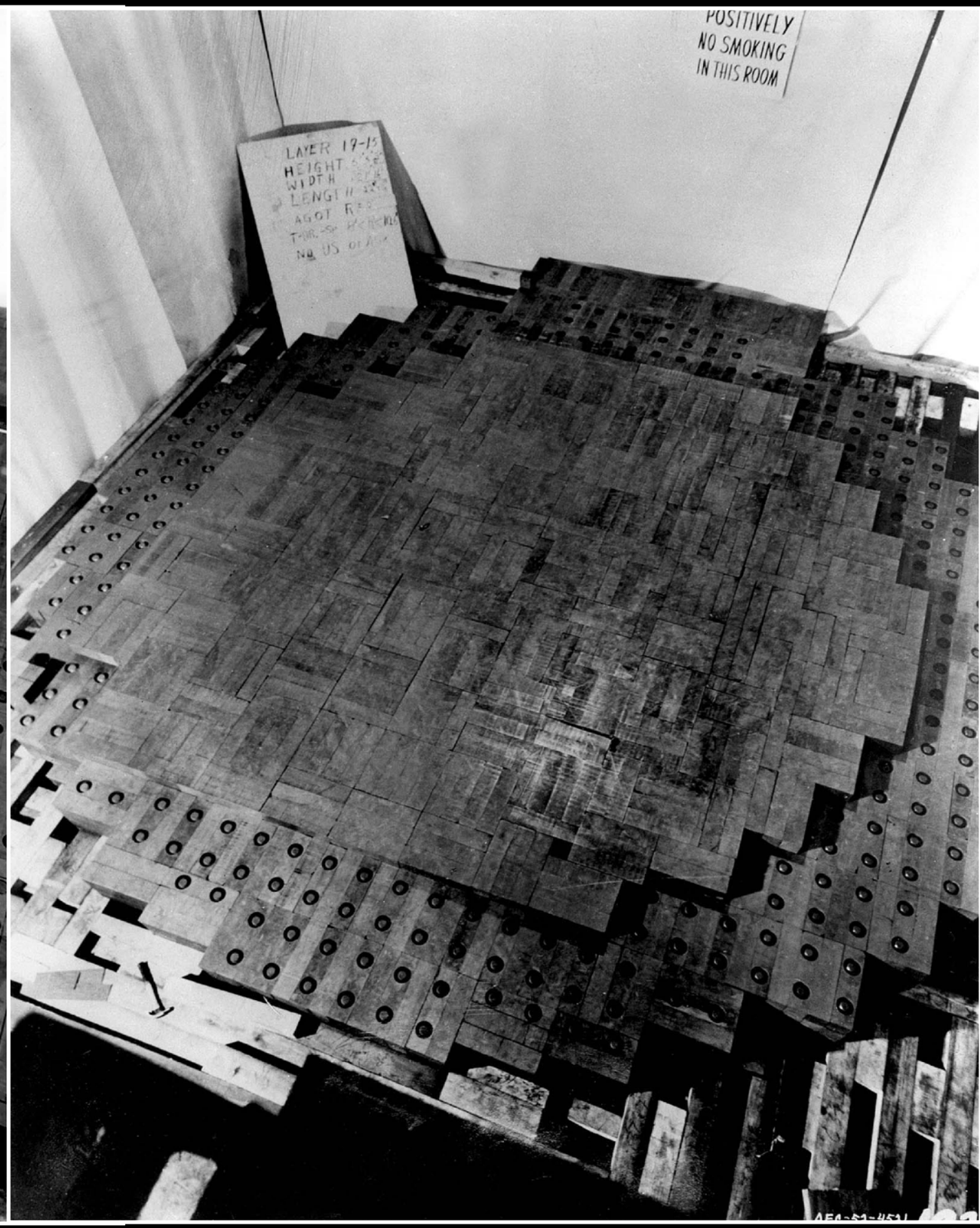
And this answer would have been wrong.
So I assumed the responsibility myself.”

Building CP-1



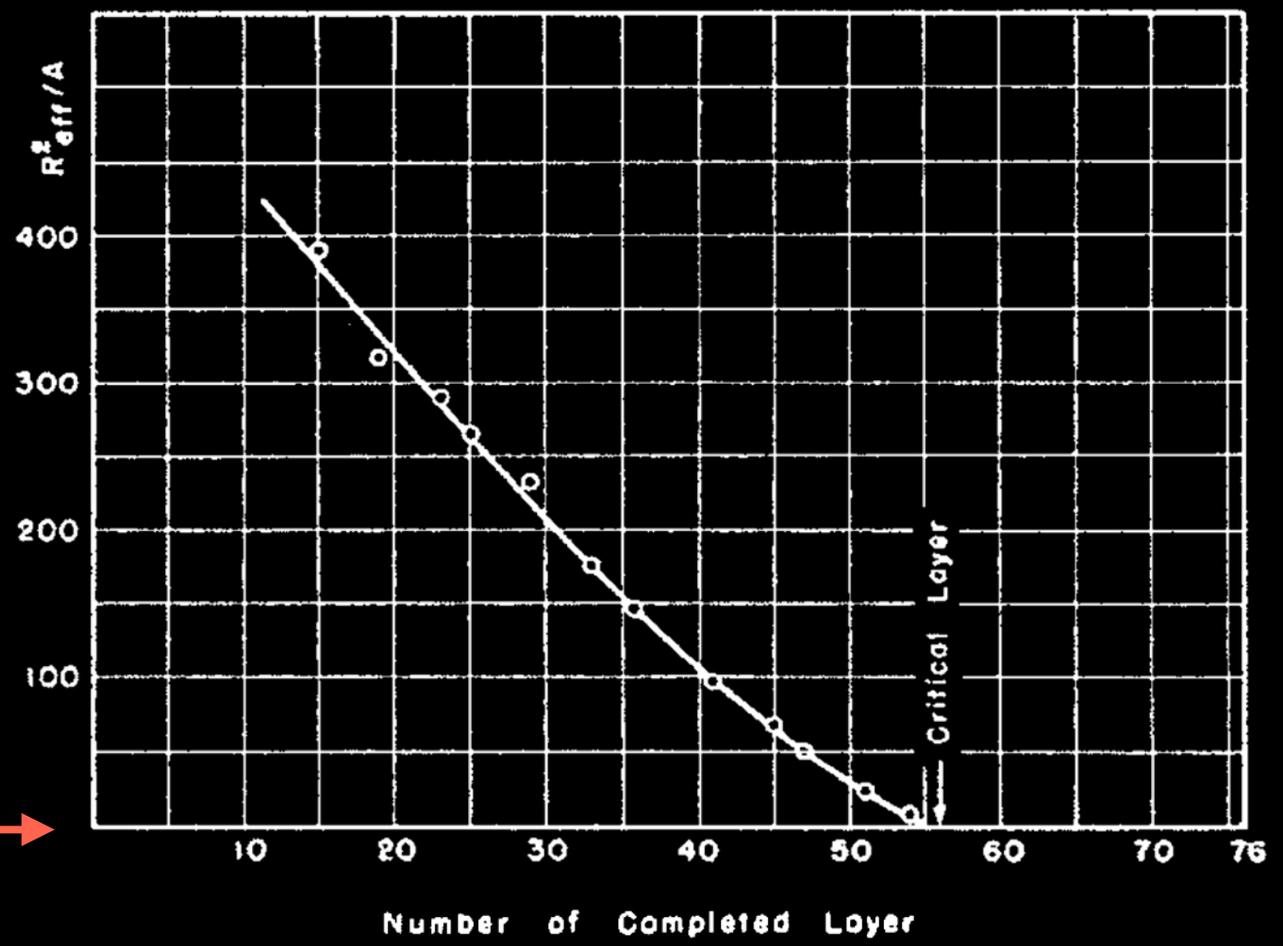


Building CP-1: layer by layer

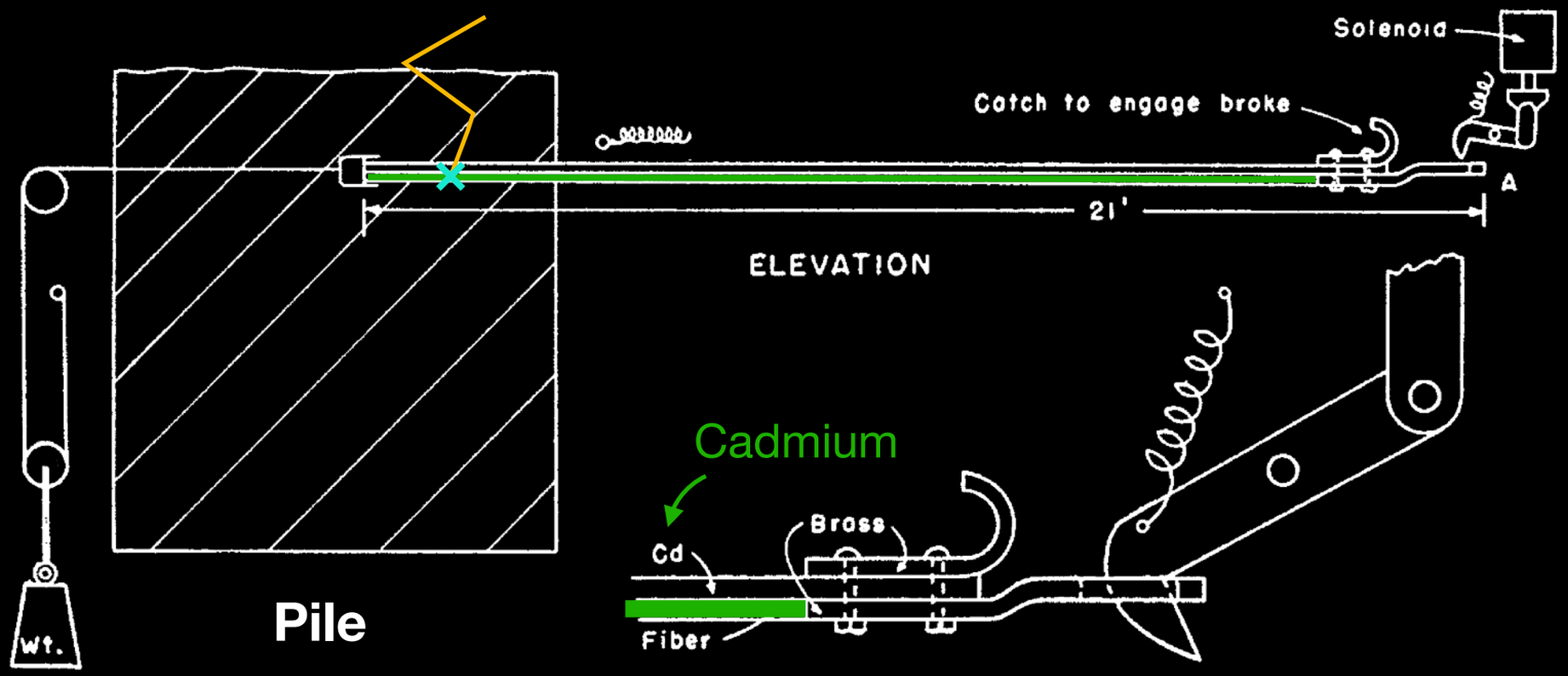


Approaching criticality … safely

Reaction becomes self-sustaining
(“Pile becomes critical”)

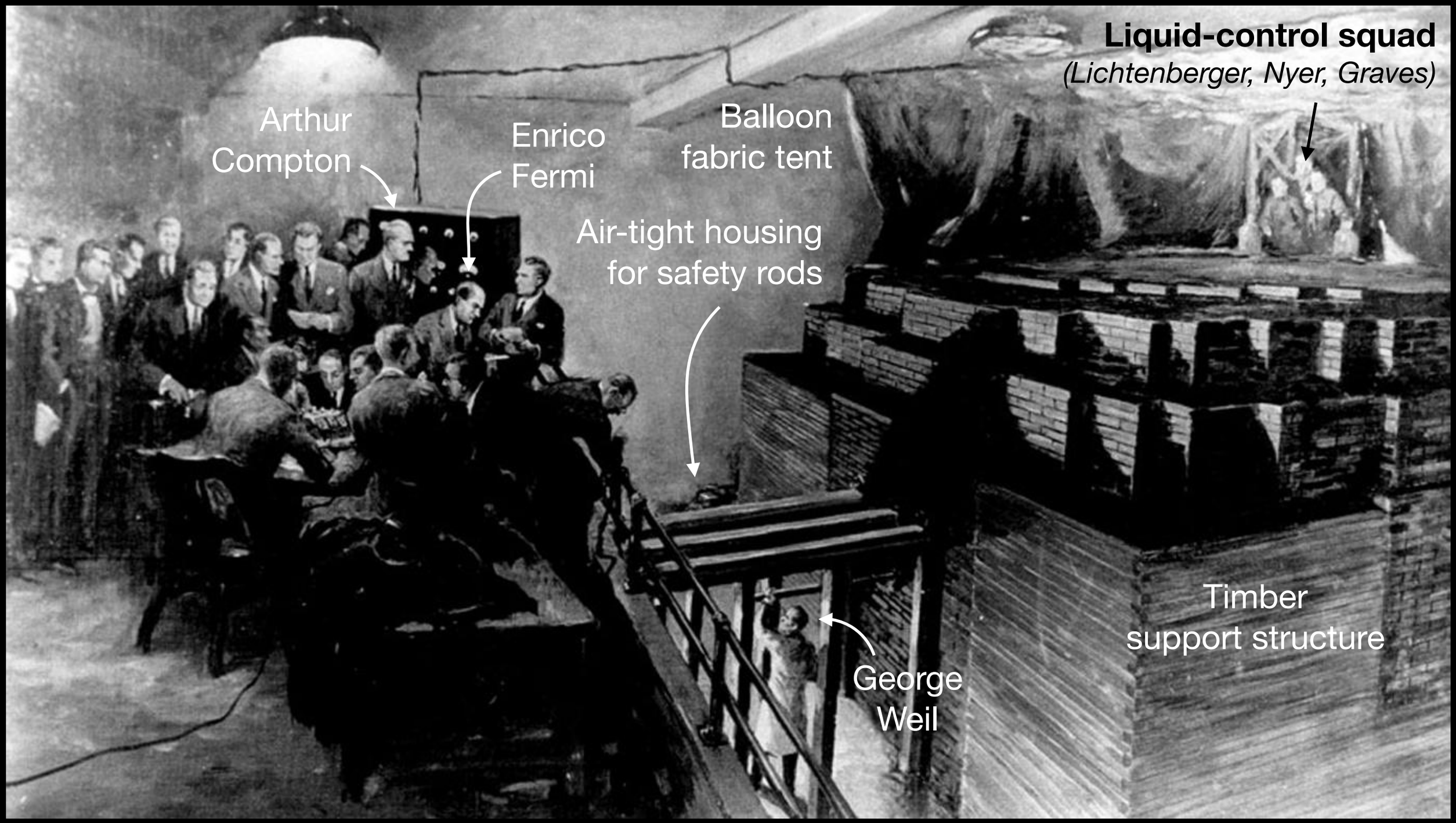


Neutron-absorbing “‘Zip’ rod”:



Magnetic hook, automatically released

December 2, 1942



December 2, 1942

"'Zip' out"

"This is not it. The trace will go to this point and level off."

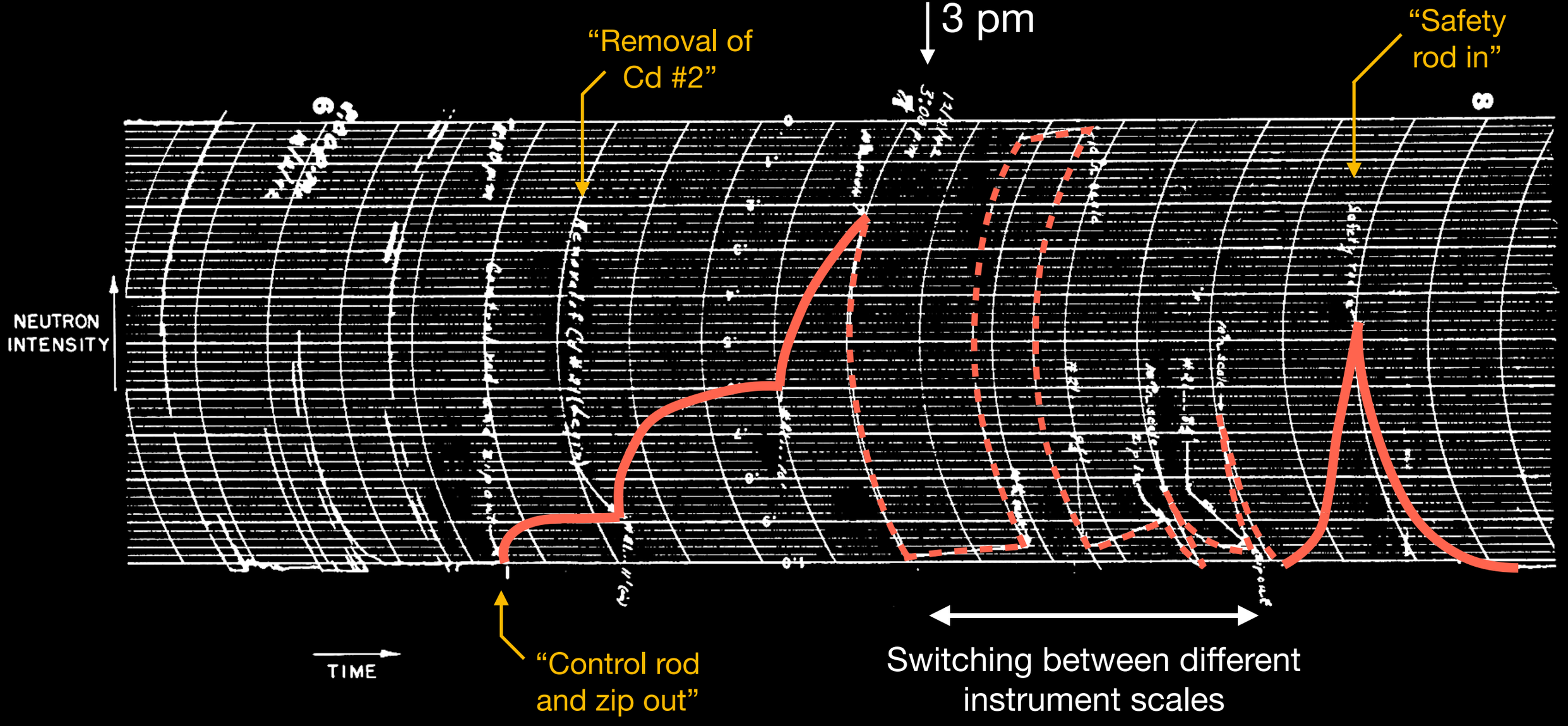
"Pull it to 13 feet, George."

"This is going to do it."

"Now it will become self-sustaining. The trace will climb and continue to climb. It will not level off."

"Pull it out another foot."

"O.K. 'Zip' in"



December 2, 1942

3.25 pm

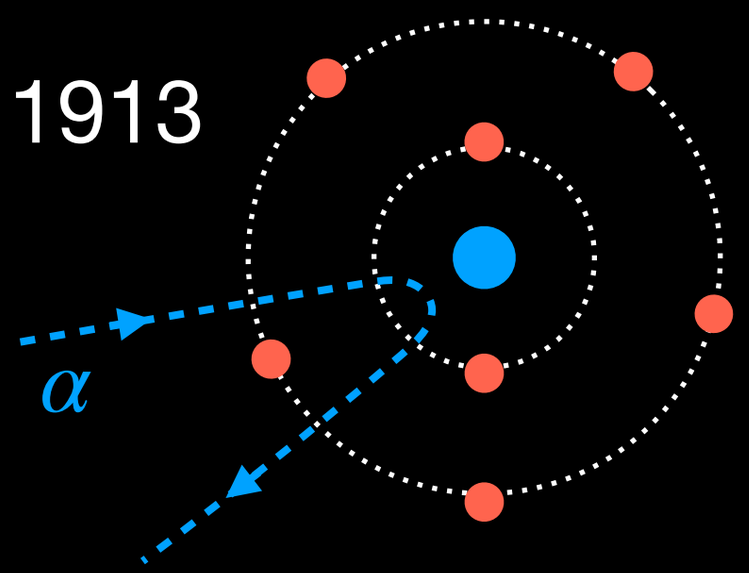
An impromptu celebration with Italian red wine and paper cups …

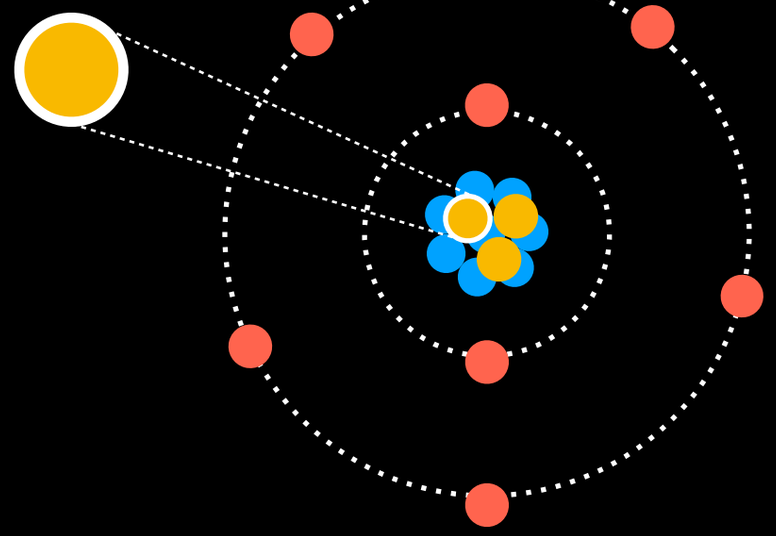
Yesterday's science is today's engineering

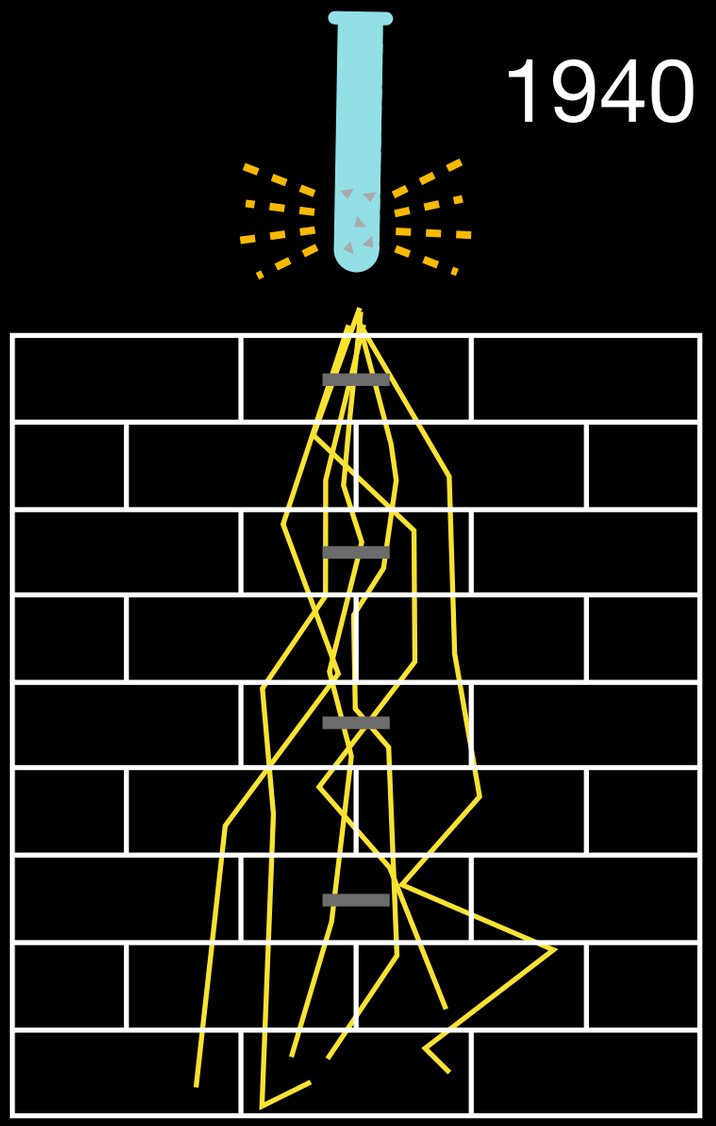
1913

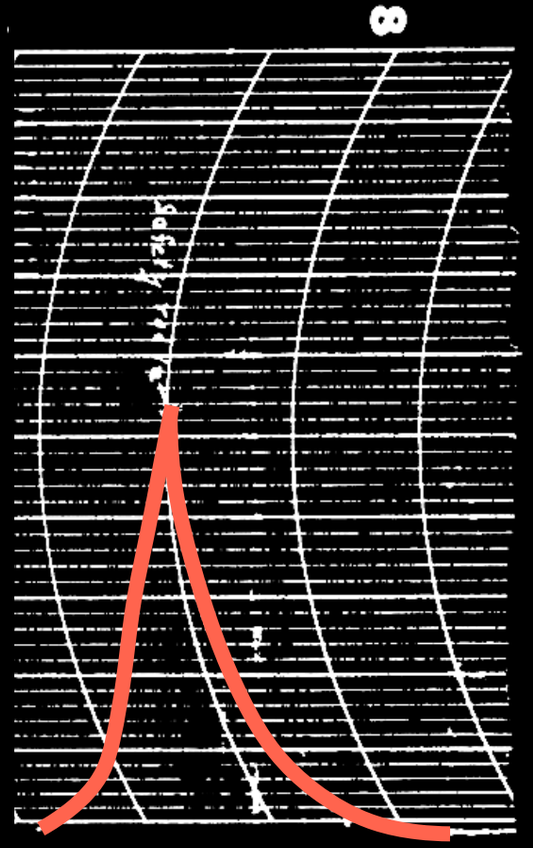
1933

1940









1942

(My) references

1. W. Crookes, “The Bakeries Lecture: On the Illumination of Lines of Molecular Pressure, and the Trajectory of Molecules” (1878)
2. J. J. Thomson, “Recent Researches in Electricity And Magnetism”, Clarendon Press (1893)
3. D. D. Patton, “Roentgen and the ‘New Light’—Roentgen’s Moment of Discovery”, Investigative Radiology 28, 10, 954—961 (1993)
4. M. Sekiya, M. Yamasaki, “Antoine Henri Becquerel: A scientist who endeavored to discover natural radioactivity”, Radiol. Phys. Technol. 8, 1—3 (2015)
5. F. W. Aston, “Isotopes”, Edward Arnold & Co (1922)
6. J. L. Heilbron, “Ernest Rutherford And the Explosion of Atoms”, Oxford University Press (2003)
7. H. E. Roscoe, A. Harden, “A New View of the Origin of Dalton’s Atomic Theory; A Contribution to Chemical History”, Macmillan And Co. (1896)
8. D. N. Schwartz, “The Last Man Who Knew Everything: The Life and Times of Enrico Fermi, Father of th the Nuclear Age”, Basic Books (2017)
9. A. Wattenberg, “The Birth of the Nuclear Age”, Physics Today 46, 44—51 (1993)
10. L. Woods, “The Uranium people”, Crane, Russia (1979)