Introduction to nuclear physics

Prof. Antoine GUITTON

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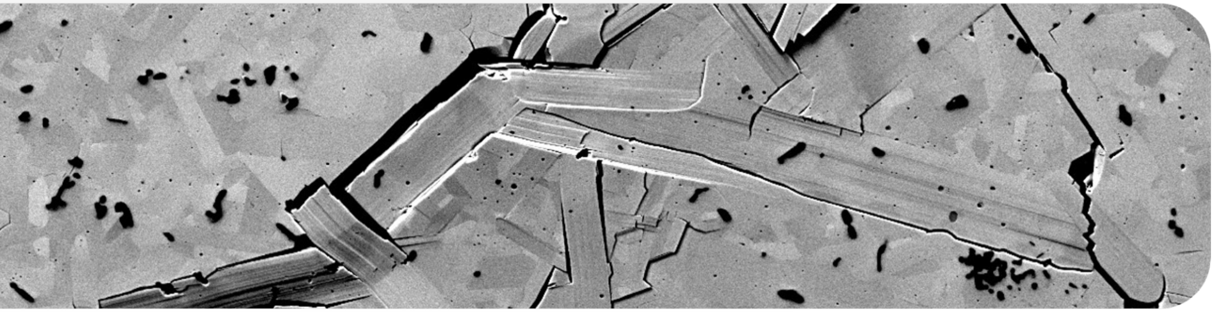

5th Century BCE

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Eleatic philosphy

- **Founders:** Παρμενίδης/Parmenides (6th BCE – 5th BCE)
  Ζήνων/Zeno (490 BCE – 430 BCE)
- **Core idea:** Reality is singular, eternal, and unchanging.
- **View on change:** Change, motion, and plurality are illusions.
- **Key argument:** Non-being cannot exist, so void (empty space) and division are impossible.
- **Perception:** Reality fundamentally differs from the sensory world.

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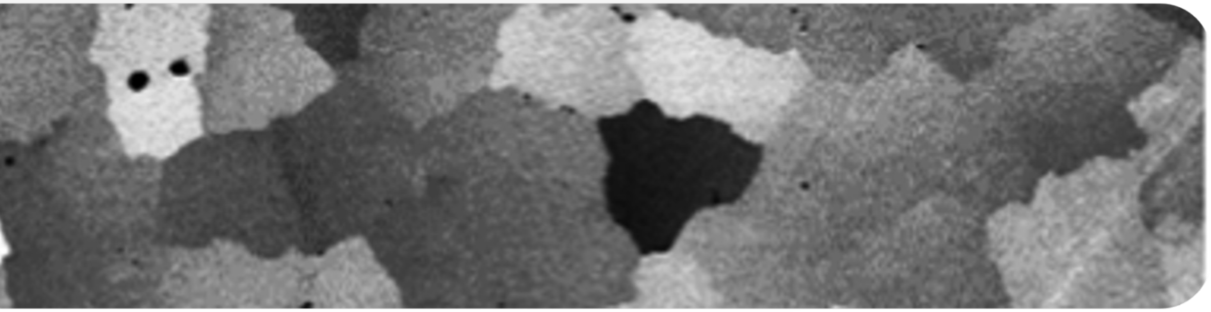
Atomism philosophy

- **Founders:** Λεύκιππος/Leucippus (5th BCE)
  Δημόκριτος/Democritus (460 BCE – 370 BCE)
- **Core idea:** Reality consists of multiple, indivisible particles (ἄτομος) and the void.
- **View on change:** Change and motion are real, arising from the interaction of atoms.
- **Key argument:** The void (empty space) is necessary for atoms to move and combine.
- **Perception:** Reality is based on multiplicity and change, rooted in atomic interactions.

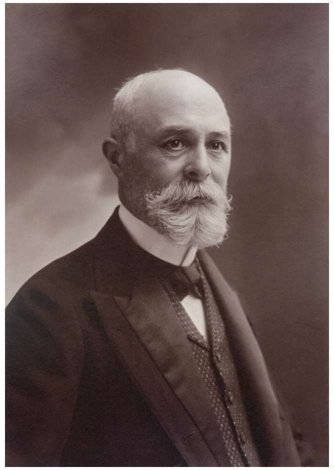


19^{th} Century

Chronology of the constituents of the atom

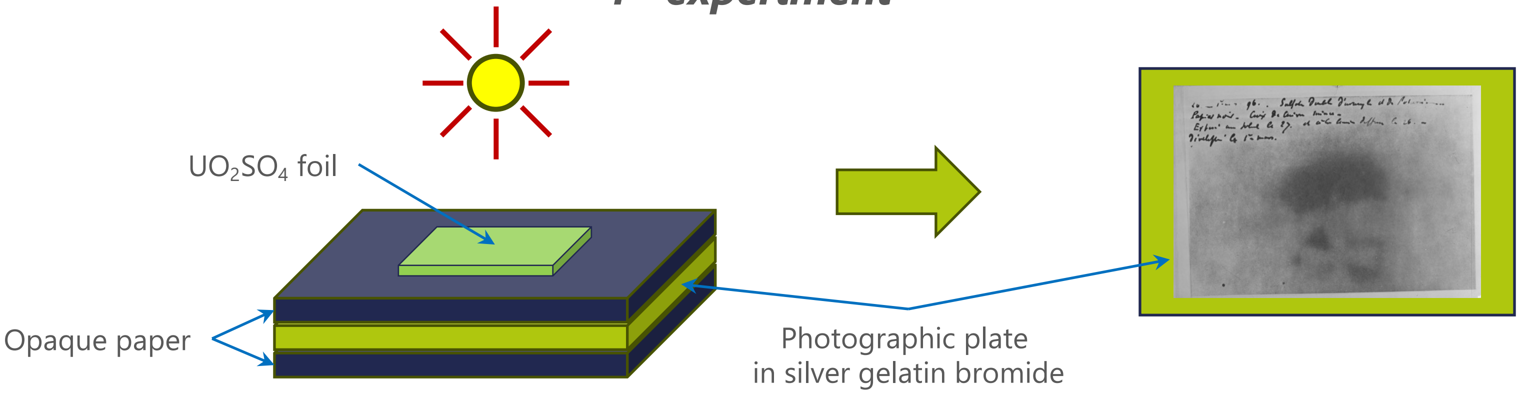
5th century BCE	• Greek philosophers introduced the idea of atoms.
1803/1808	• J. Dalton theorized that each element is composed of atoms.

Discovery of natural radioactivity



Henri BECQUEREL
(1852 – 1908) 🇫🇷
1/3 Nobel Prize (1903)

1st experiment



H. Becquerel, *C. R. Acad. Sci.* (1896)

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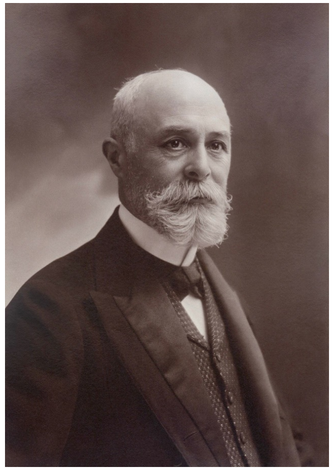

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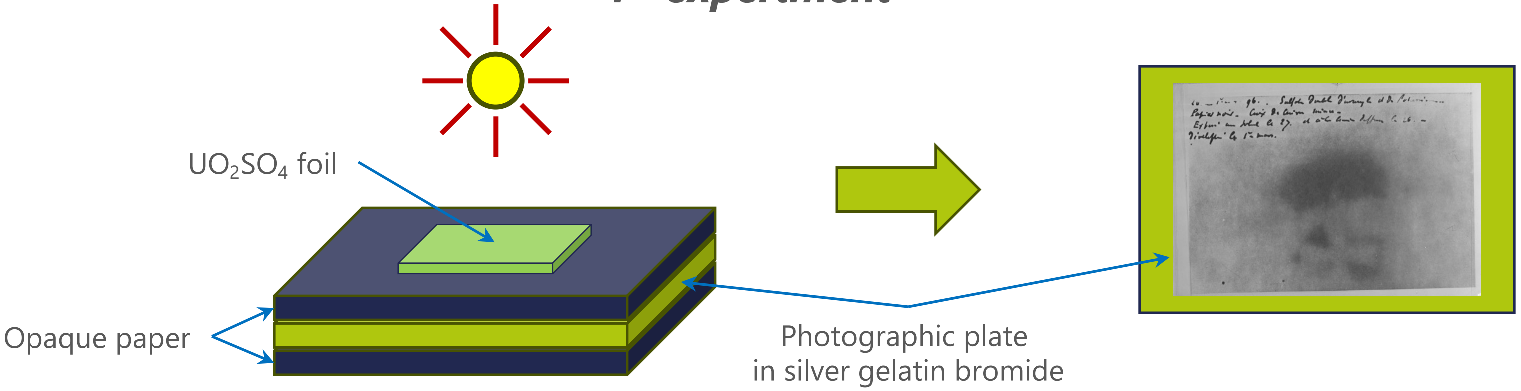
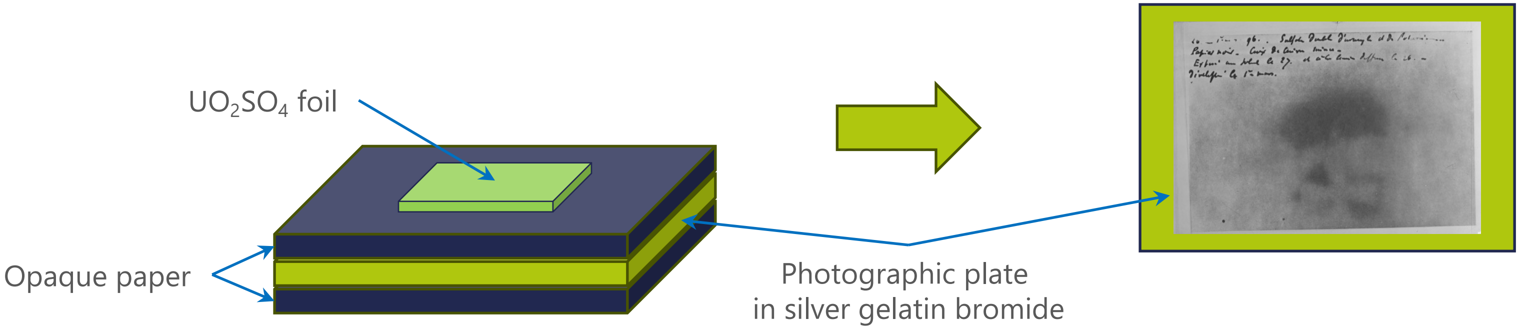


2nd experiment



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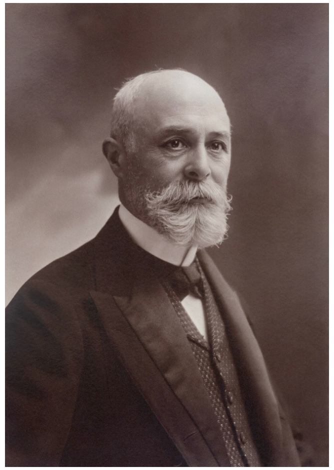

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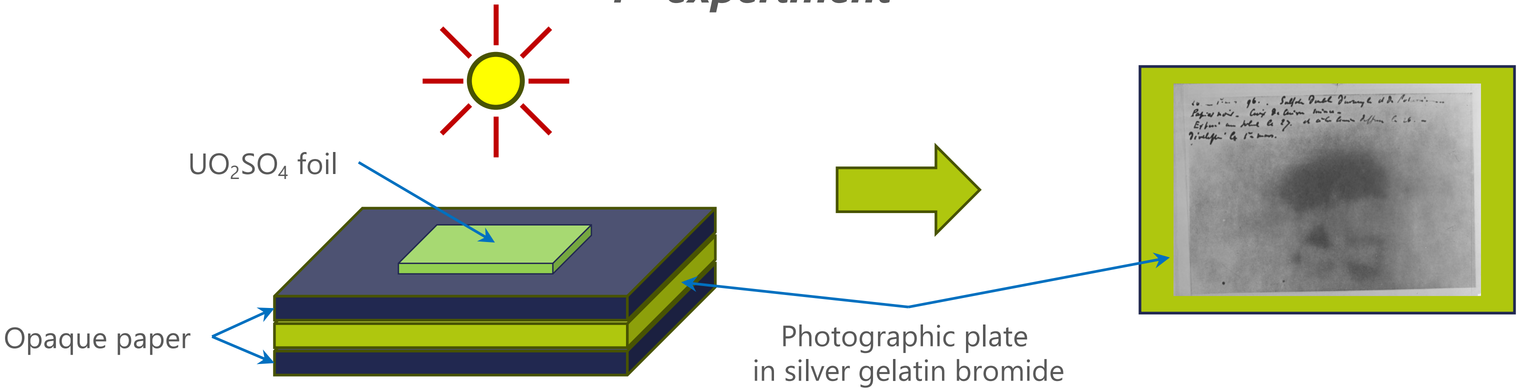

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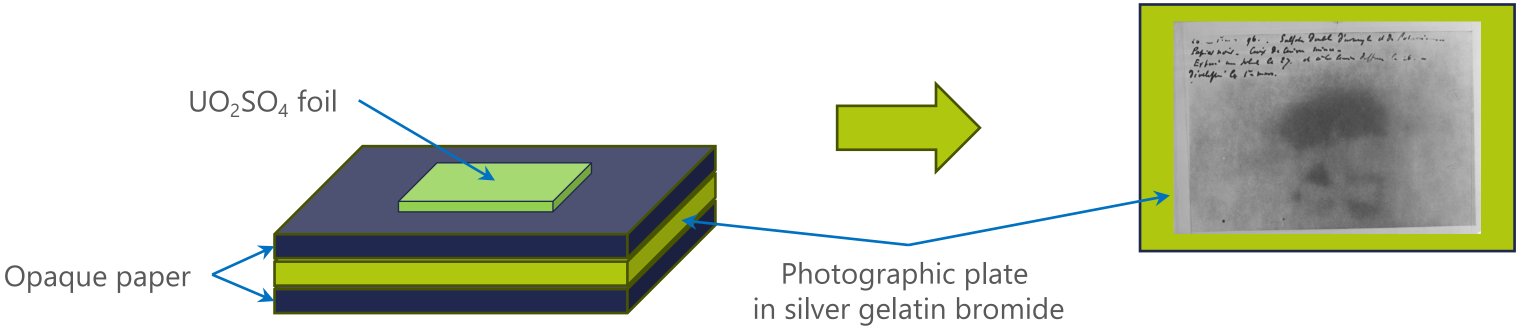

» Une hypothèse qui se présente assez naturellement à l'esprit serait de supposer que ces radiations, dont les effets ont une grande analogie avec les effets produits par les radiations étudiées par MM. Lenard et Röntgen, seraient des radiations invisibles émises par phosphorescence, et dont la durée de persistance serait infiniment plus grande que la durée de persistance des radiations lumineuses émises par ces corps. Toutefois, les expériences présentes, sans être contraires à cette hypothèse, n'autorisent pas à la formuler. Les expériences que je poursuis en ce moment pourront, je l'espère, apporter quelques éclaircissements sur ce nouvel ordre de phénomènes. »

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"Radiations studied by M. Röntgen"

❖ **On the evening of November 8, 1895, in Würzburg, Germany:**

- Röntgen made a screen fluoresce near a Crookes tube inside a black box.
- Then, he played with various objects revealing their transparency.

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Since Röntgen did not understand their nature, he called these rays, X-rays!

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The radioactivity

- **1896:**
  - Becquerel showed that uranium rays make the air conductive.

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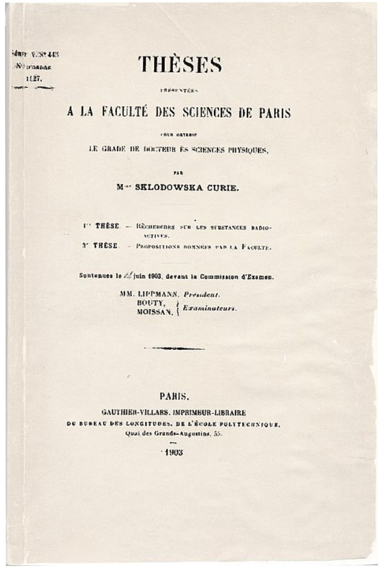

THÈSES

PRÉSENTÉES

A LA FACULTÉ DES SCIENCES DE PARIS

POUR OBTENIR

LE GRADE DE DOCTEUR ÈS SCIENCES PHYSIQUES,

PAR

Mme SKLODOWSKA CURIE.

1re THÈSE. — Recherches sur les substances radio-actives.

2e THÈSE. — Propositions données par la Faculté.

Soutenues le juin 1903, devant la Commission d'Examen.

MM. LIPPMANN, *Président.*
BOUTY, MOISSAN, *Examinateurs.*

PARIS.

GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE
DU BUREAU DES LONGITUDES, DE L'ÉCOLE POLYTECHNIQUE,
Quai des Grands-Augustins, 55.

1903

H. Becquerel, *C. R. Acad. Sci.* (1896)
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- The Curies decided that the electrometer previously developed by Pierre Curie could help measure the intensity of the emitted radiation.
- Marie Curie perfected this method by combining chemical techniques to isolate the samples with measurements of electrical conductivity.

The Curies succeeded in precisely quantifying the intensity of the emitted radiation, which proved crucial in identifying elements more radioactive than uranium, such as polonium and radium.

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↳ They proposed the term "radioactivity".

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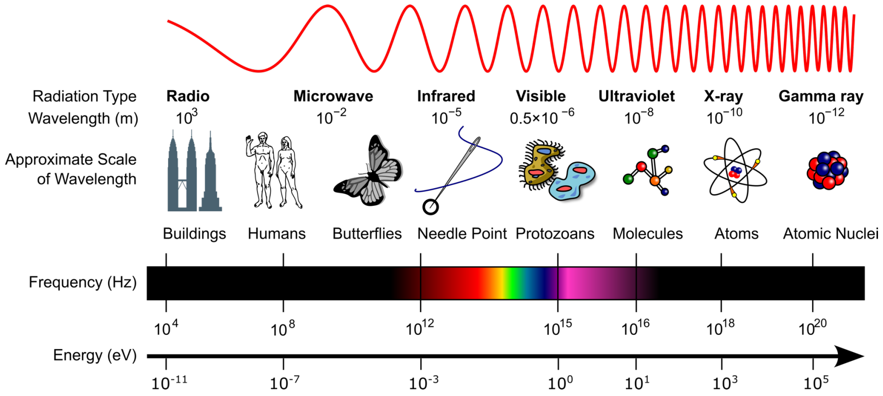
Ionizing radiations

Uranium rays make the air conductive…

Ionizing radiation

- It consists of subatomic particles or electromagnetic waves with enough energy (E_{rad}~ 10 keV) to remove electrons from atoms or molecules, thereby ionizing them (E_{ion}~ 10 eV).

$$1\ eV = 1.60\times10^{-19}\ \mathrm{J}$$



$$E = h\nu = \hbar\omega$$

where h: Planck's constant; ν:frequency; ω: pulsation

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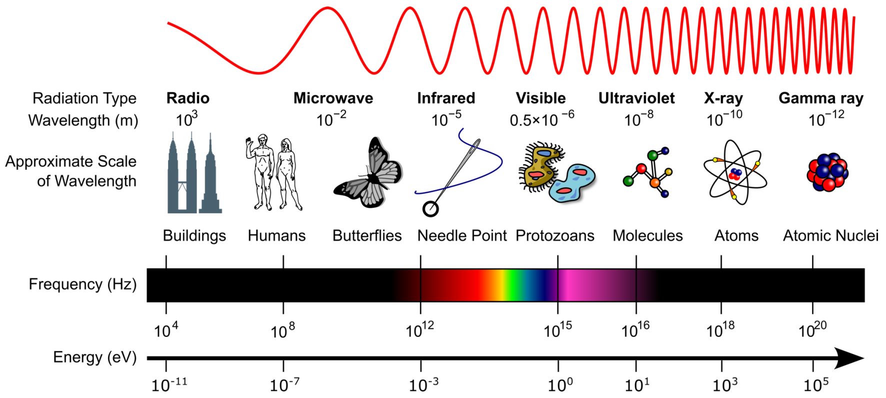

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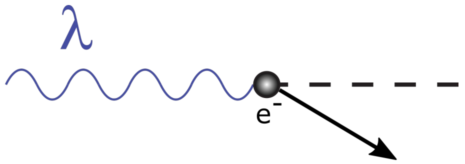
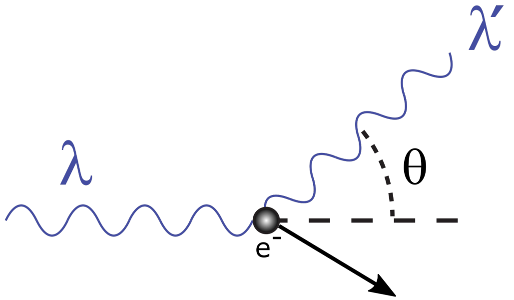
Photon-matter interaction

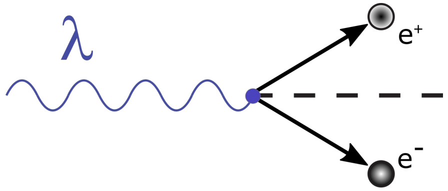
- **Photoabsorption effect:** A photon transfers all its energy to an electron, ejecting it if the energy exceeds the electron's binding energy.



- **Compton scattering:** An incident photon collides with a free or loosely bound electron, losing energy and changing direction. The electron gains this energy and is ejected with a new direction and velocity.



- **Pair production:** A high-energy photon interacts with an atom's nucleus and converts into an electron-positron pair.



Irradiated vs. contaminated and units

- **Irradiated vs. Contaminated:**
  - *Irradiation:*
    - ✓ Exposure to radiation without direct contact with the radioactive source.
    - ✓ Stops when the source is removed.
    - ✓ Example: X-ray, standing near radioactive material.

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Unit	What it measures	Orders of magnitude
Becquerel (Bq)	**Radioactivity (activity):** number of nuclear decays per second (1 Bq = 1 decay/s). Does not indicate radiation type or energy.	1 Bq (very weak) → 10^{12} Bq (highly radioactive source)
Gray (Gy)	**Absorbed dose: energy deposited per kg of material by radiation (1 Gy = 1 J/kg):** measures physical energy transfer but does not account for biological effects.	0.001 Gy (chest X-ray) → 5 Gy (lethal dose)
Sievert (Sv)	**Biological effect (dose equivalent & effective dose):** adjusted dose based on radiation type and irradiated material/tissue sensitivity. 1 Sv = 1 Gy × weighting factors for radiation and tissue type.	0.001 Sv (X-ray) → 10 Sv (fatal exposure in hours)

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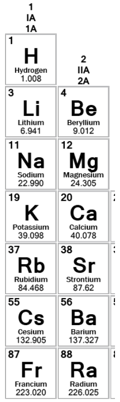
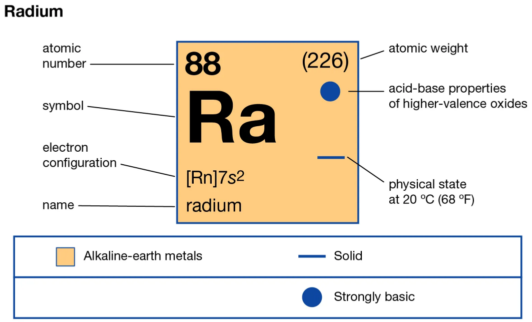
Corium – the elephant foot (Chernobyl):
- $\sim 10^{17}$ Bq
- ~100 Gy/h (death in 3 min)
- ~100 Sv/h

Focus on the radium





- **Appearance:** Silvery-white metal, but quickly oxidizes to black when exposed to air
- **Radioactivity:** Highly radioactive
- **Occurrence:** Found in uranium and thorium ores, especially in pitchblende
- **Chemical properties:** Reacts with water to form radium hydroxide, similar to other alkaline earth metals

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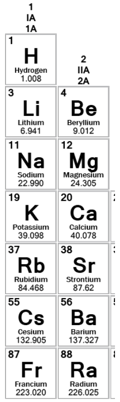

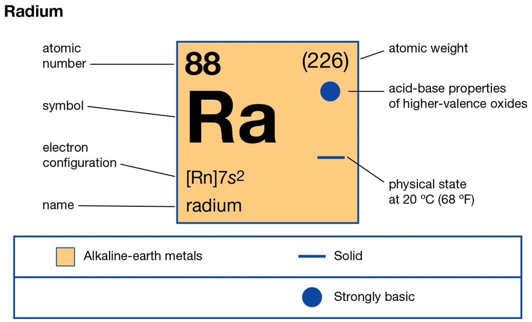


UNITED STATES PATENT OFFICE.

GEORGE F. KUNZ, OF NEW YORK, N. Y.

LUMINOUS COMPOSITION.

SPECIFICATION forming part of Letters Patent No. 789,811, dated May 16, 1905.

Application filed September 24, 1903. Serial No. 174,492. (Specimens.)

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- **Radioactivity:** Highly radioactive
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- **Chemical properties:** Reacts with water to form radium hydroxide, similar to other alkaline earth metals
- **Historical uses:** Previously used in luminescent paints, medical treatments, and industrial applications
- **Health risks:** Highly toxic; exposure can cause radiation sickness, cancer, and bone damage
- **Regulation & decline in use:** By the mid-20th century, the dangers of radium became widely recognized, leading to strict regulations and the discontinuation of its commercial applications.
- **Modern uses:** Limited to scientific research and some medical applications (e.g., cancer treatment with radium-223)

Nature of radiations

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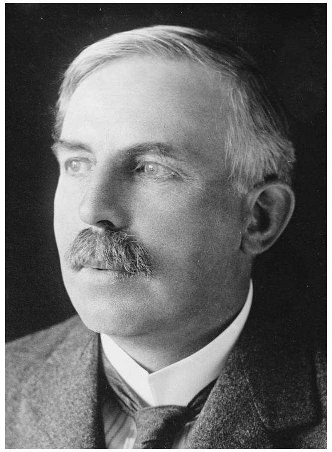
  - Rutherford sought to understand the nature of the radioactive emissions from uranium, similar to Röntgen's work on X-rays



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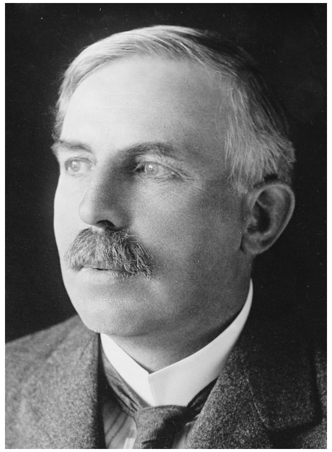

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  - He observed two types of radiations:
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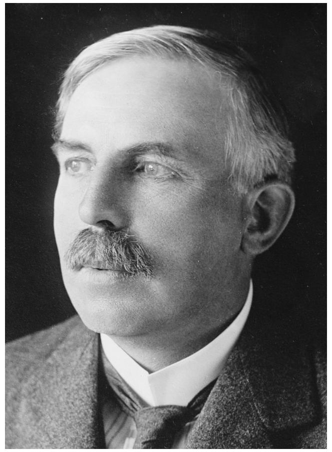
$\Rightarrow$ α **particles**



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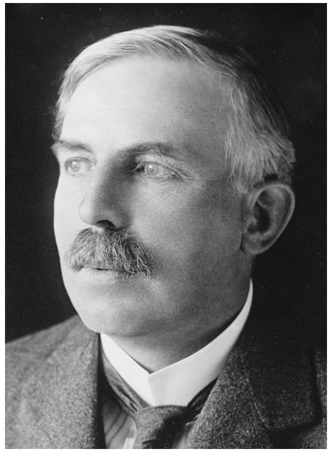
    ⇒ **α particles**

  - ✓ *2nd type:* These were much more penetrating, passing through several millimeters of metal or dense material. They were deflected by the magnetic field, indicating they carried a negative charge.

    ⇒ **β particles**



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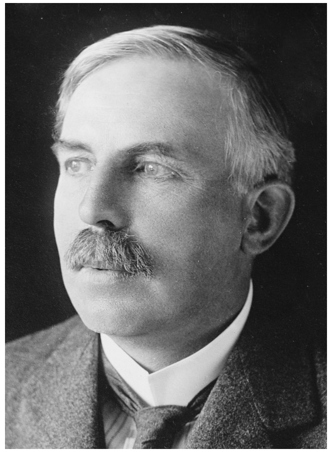

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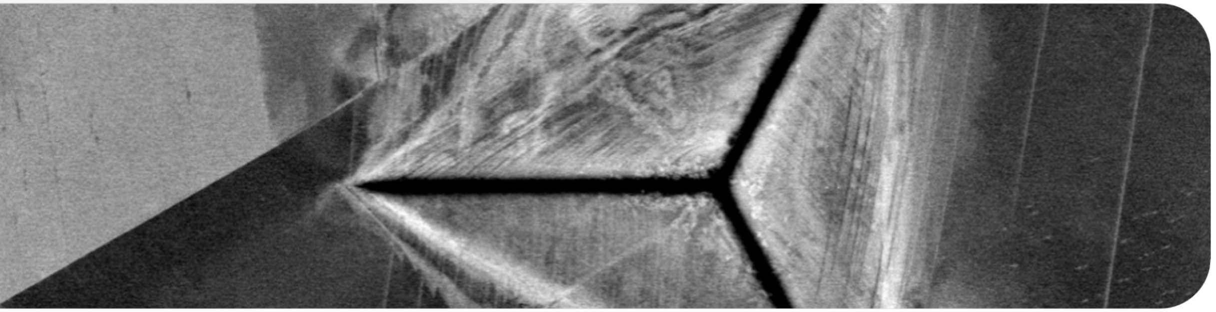
↳ 2 types of radiation: $\boldsymbol{\alpha}$ (later identified as helium nuclei by Rutherford & Royds in 1909) and $\boldsymbol{\beta}$ (the β^- particle was identified as an electron by Becquerel as early as 1900, via its charge-to-mass ratio).

E. Rutherford, *Philos. Mag.* (1899)

Chronology of the constituents of the atom

5^{th} century BCE	• Greek philosophers introduced the idea of atoms.
1803/1808	• J. Dalton theorized that each element is composed of atoms.
1897	• J.J. Thomson discovered the electrons as negative particles.



And now, let's continue to

20th Century

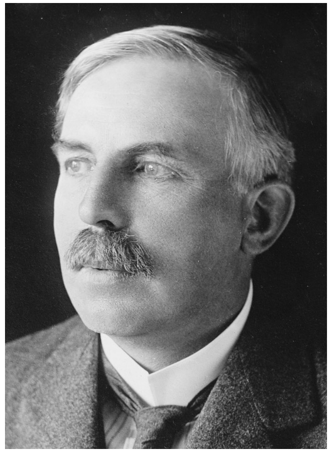
The transmutation

❖ **1902:**

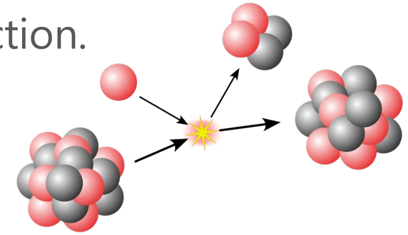
- Radioactive elements undergo spontaneous changes, transmuting into new elements over time.
- This process follows a well-defined sequence rather than being a reversible reaction.

$$X_1 \rightarrow X_2 \rightarrow X_3 \rightarrow \cdots \rightarrow X_{stable}$$

- Radioactivity is linked to atomic transformation, not just energy emission.



Ernest RUTHERFORD
(1871 – 1937)
1 Nobel Prize (1908)



E. Rutherford and F. Soddy, *Philos. Mag.* (1902)

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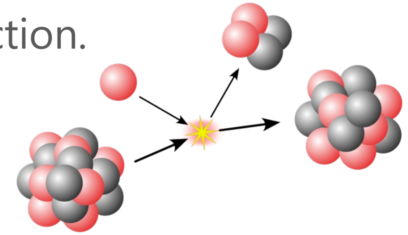

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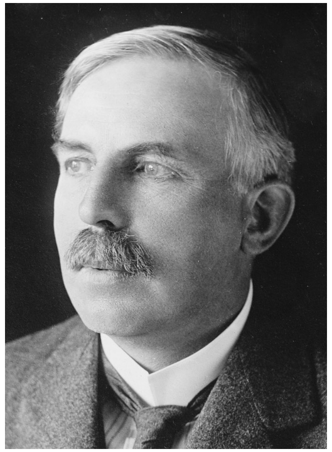

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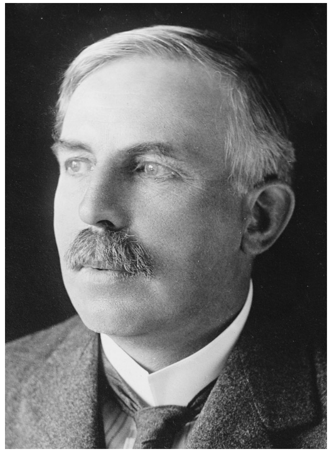

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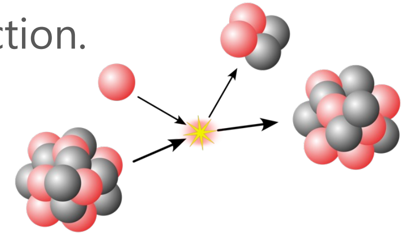

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$${}^{A}_{Z}X$$ (Z: number of protons; A: number of nucleons)

  - Each transformation emits radiation (α or β particles).
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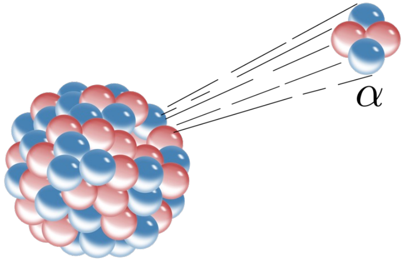
$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha(= {}^{4}_{2}He)$$



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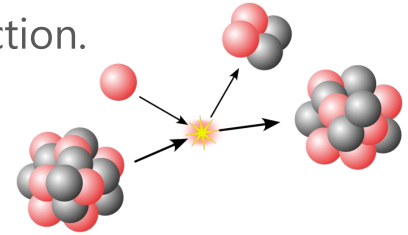

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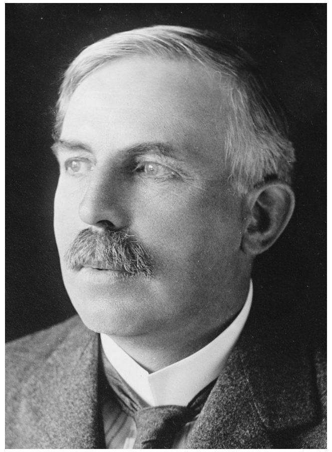

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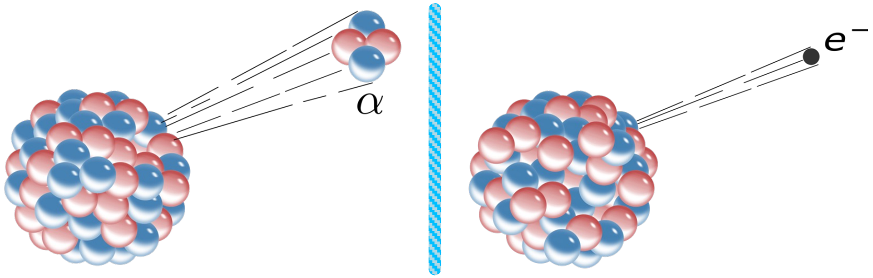

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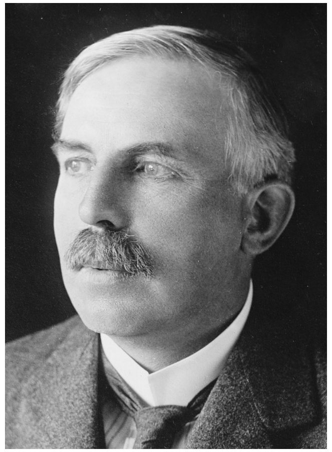

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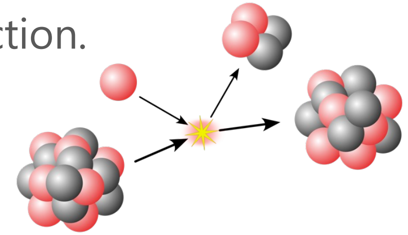

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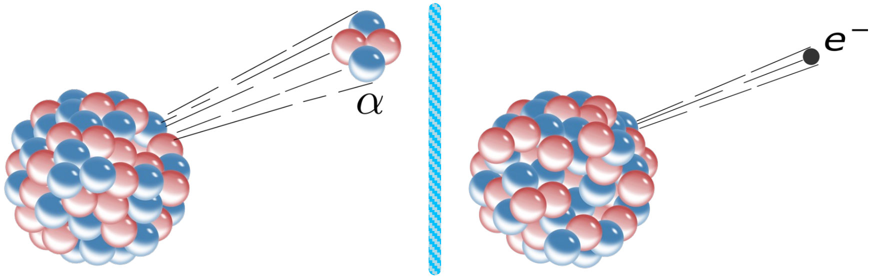


Atoms are not indivisible, as previously thought, but undergo fundamental transformations.

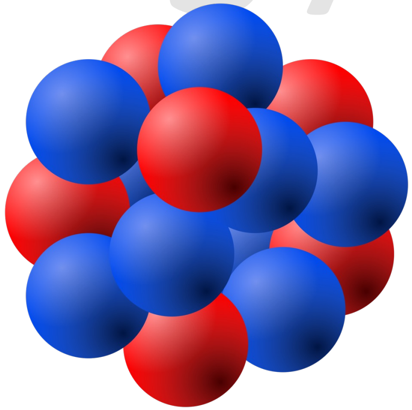
E. Rutherford and F. Soddy, *Philos. Mag.* (1902)

Chronology of the constituents of the atom

5^{th} century BCE	• Greek philosophers introduced the idea of atoms.
1803/1808	• J. Dalton theorized that each element is composed of atoms.
1897	• J.J. Thomson discovered the electrons as negative particles.
1911	• E. Rutherford showed that most of the atom's mass and positive charge is concentrated in a central nucleus.
1919	• E. Rutherford proposed that the nucleus contains a fundamental, positively charged particle, the proton.
1932	• J. Chadwick identified the neutral particle, the neutron. • C. Anderson discovered the positron, the first antimatter particle.

Focus on the nucleus

$^{A}_{Z}X$ Z: number of **protons** ⊕; A: number of nucleons (**protons** ⊕+ **neutrons** ⓪)



❖ **Isotopes?**

- They are nuclei of the same element that have the same number of **protons** ⊕ but different numbers of **neutrons** ⓪.
- They have the same Z but different A.

E. Fermi, *Z. Phys.* (1934)

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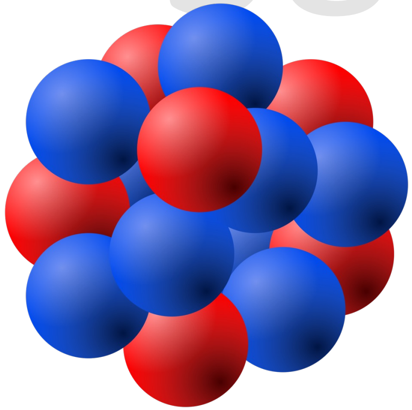

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- Some properties:
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  - ✓ Different physical properties (due to different masses; A)
  - ✓ Some isotopes are stable, while others are radioactive.

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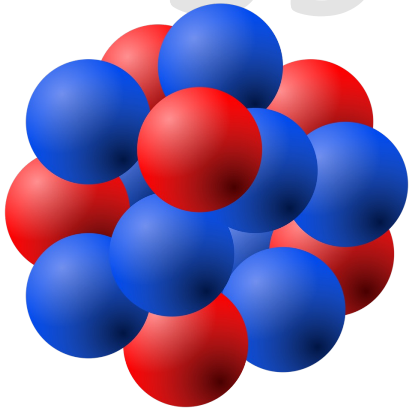

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    - ✓ Some isotopes are stable, while others are radioactive.
  - Some examples:

Element	Isotopes	Stable (S) or radioactive (☢)?
Hydrogen (H)	$^{1}_{1}H$ (protium); $^{2}_{1}H$ (deuterium); $^{3}_{1}H$ (tritium)	$^{1}_{1}H \rightarrow$ S; $^{2}_{1}H \rightarrow$S; $^{3}_{1}H \rightarrow$☢
Carbon (C)	$^{12}_{6}C$; $^{13}_{6}C$; $^{14}_{6}C$	$^{12}_{6}C \rightarrow$ S; $^{13}_{6}C \rightarrow$S; $^{14}_{6}C \rightarrow$☢
Uranium (U)	$^{235}_{92}U$; $^{238}_{92}U$	$^{235}_{92}U \rightarrow$ ☢; $^{238}_{92}U \rightarrow$☢

↳ How can positive particles (protons) stay bound together in the nucleus?

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1964	• M. Gell-Mann and G. Zweig developed the quark model.

The four fundamental interactions

- **Strong interaction:**
  - Responsible for nuclear cohesion.
  - Relative strength: 10^{39} (reference: gravitation interaction)
  - Range: 10^{-15} m
  - Mediator: gluons

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  - Responsible for the large-scale structure and dynamics of the universe.
  - Relative strength: 1 (reference: gravitation interaction)
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  - Responsible for the β decay.
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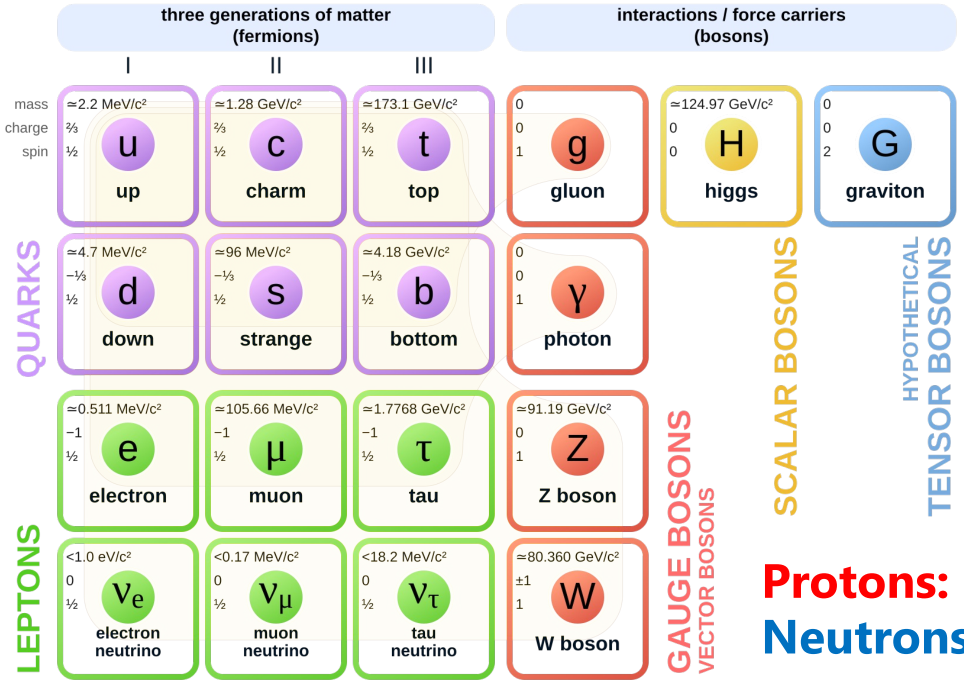

Protons: uud
Neutrons: udd

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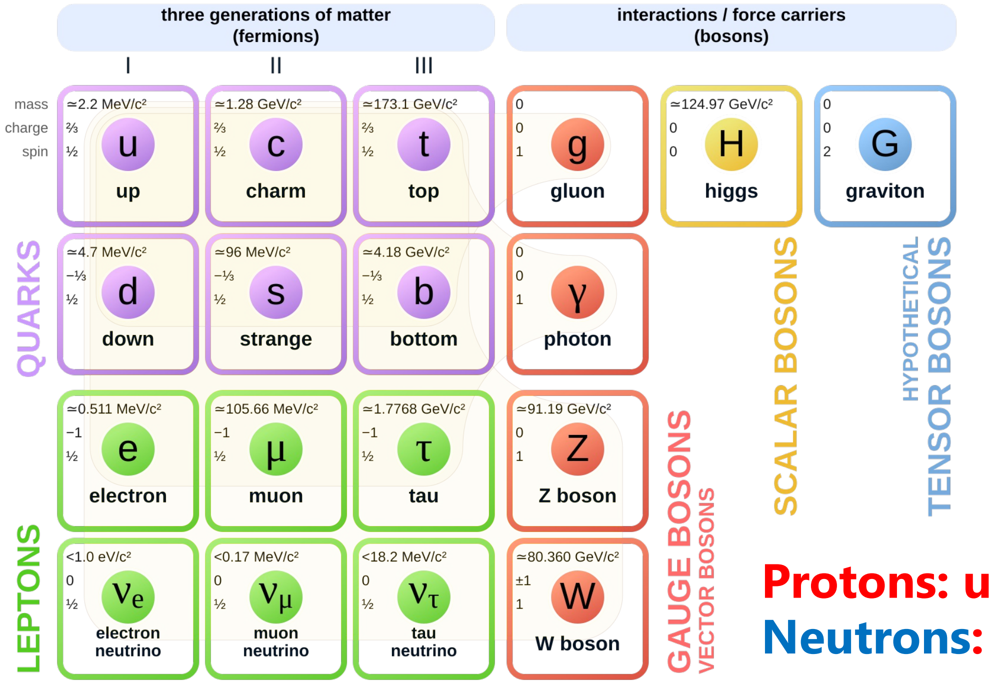

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Focus on the β decay

Enrico FERMI
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  - β^-: a neutron converts into a proton, emitting an electron and an antineutrino ($\bar{\nu}_e$)

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↳ The β decay does not change nucleon number (A), but changes atomic number (Z).

E. Fermi, *Z. Phys.* (1934)

The γ emmission

Paul VILLARD
(1860 – 1934) 🇫🇷

- **1900:**
  - Paul Villard was studying the radioactivity of radium.
  - He identified a highly penetrating radiation, different from the α and β particles discovered by Becquerel and Rutherford.
  - He showed that this radiation was not deflected by a magnetic field, suggesting a neutral and electromagnetic nature.

    ↳ **This radiation was later named "γ rays", in analogy with α and β particles.**

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❖ **Some characteristics of the γ rays:**

- γ emission is the electromagnetic radiation released by an excited nucleus after a nuclear decay.
- Unlike α or beta β decay, it does not change the number of protons or neutrons (Z and A remain constant)
- The resulting nucleus is often in an excited state and emits a γ photon to reach its ground state.
- Highly energetic (keV to MeV range).
- Weakly absorbed by matter. But can be stopped by lead or concrete.

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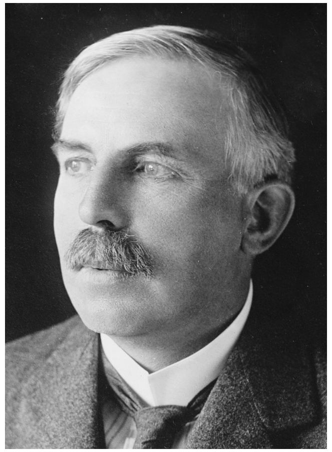
Example:

$$^{60}_{27}Co \xrightarrow{\beta^-} {}^{60}_{28}Ni^* + {}^{0}_{-1}e^- + \bar{\nu}_e$$

$$^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni + \gamma$$

P. Villard, *C. R. Acad. Sci.* (1900)

The decay law



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- **1902:**
  - The decay rate is constant.

(*N*: number of nuclei; *λ*: radioactivity constant; N_0: initial number of nuclei)

$$\frac{\Delta N(t_1 \rightarrow t_2)}{N(t_1)} = -\lambda \Delta t$$

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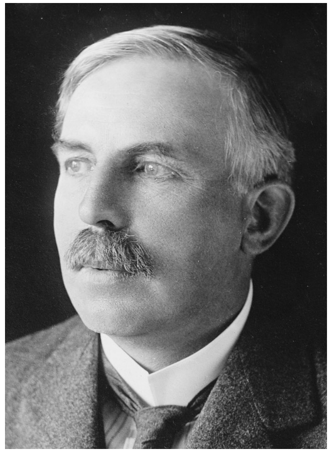

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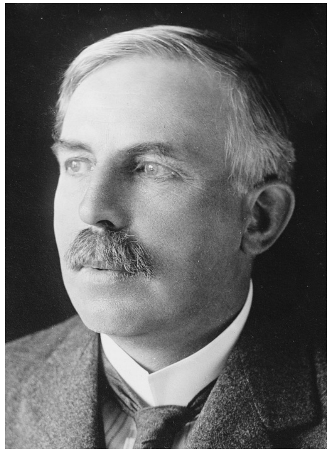

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- Half-life ($t_{1/2}$): the time required for half of the unstable nuclei in a sample to decay

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

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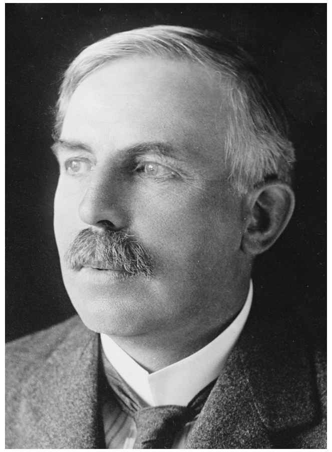

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➯ Radioactive decay is a natural predictable process with valuable applications.

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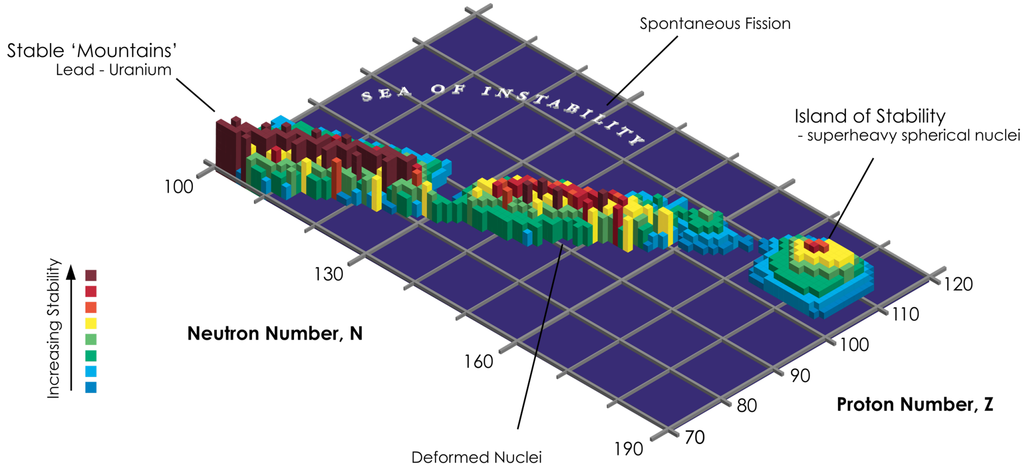
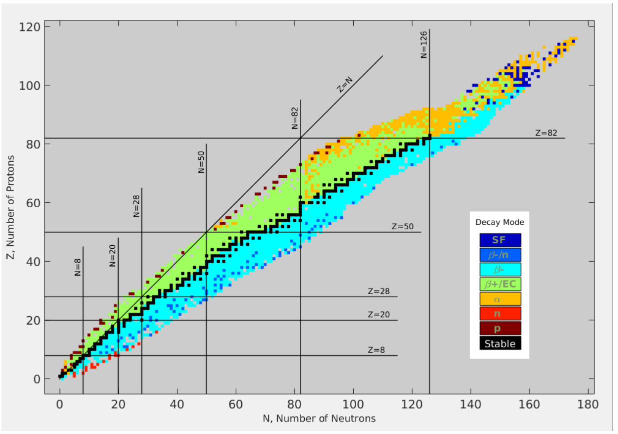
Valley of stability

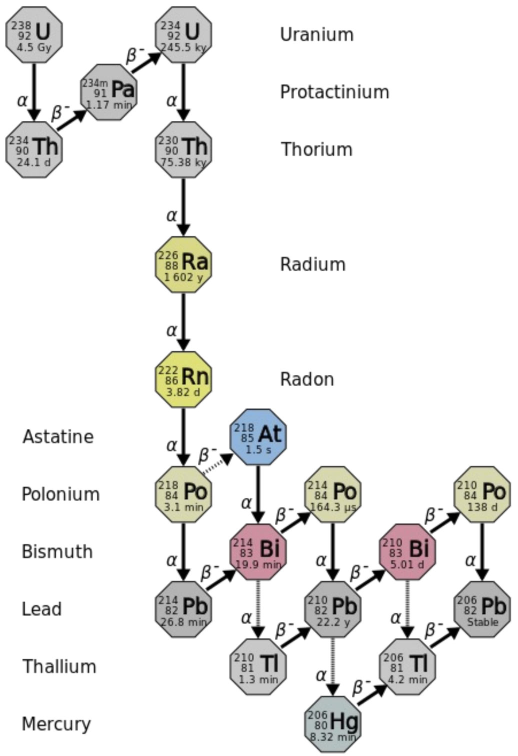
The valley of stability represents the region where atomic nuclei are stable.





- **Axes representation:**
  - X-axis: number of neutrons N
  - Y-axis: number of protons Z
- **Color scale:** indicates binding energy per nucleon, which reflects nuclear stability.
- **Stable nuclei** form a curved path in the (N, Z) plane, where the neutron-to-proton ratio is optimal.
- **Off-the-valley nuclei are unstable:**
  - Above the valley (neutron-rich nuclei): undergo β^- decay.
  - Below the valley (proton-rich nuclei): undergo β^+decay.
  - Heavy nuclei at the extreme end: undergo α decay or spontaneous fission.

The transmutation



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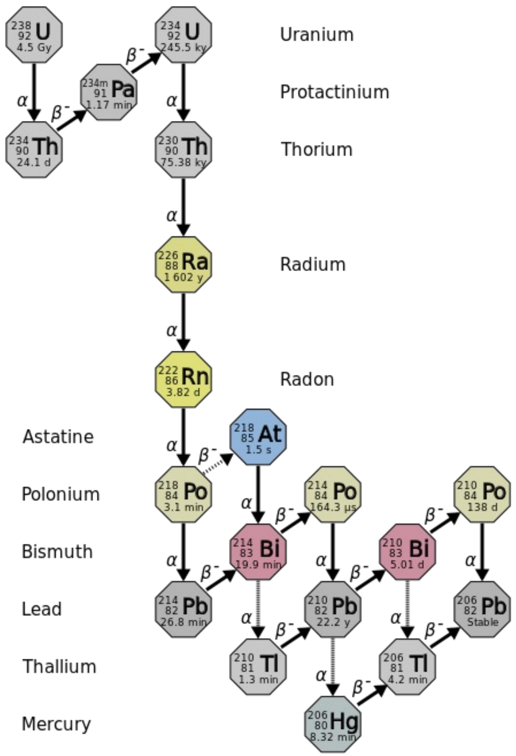

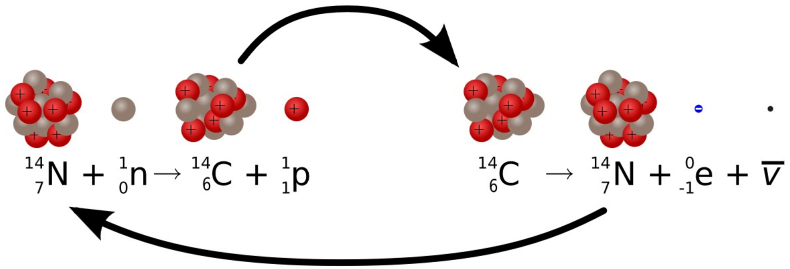

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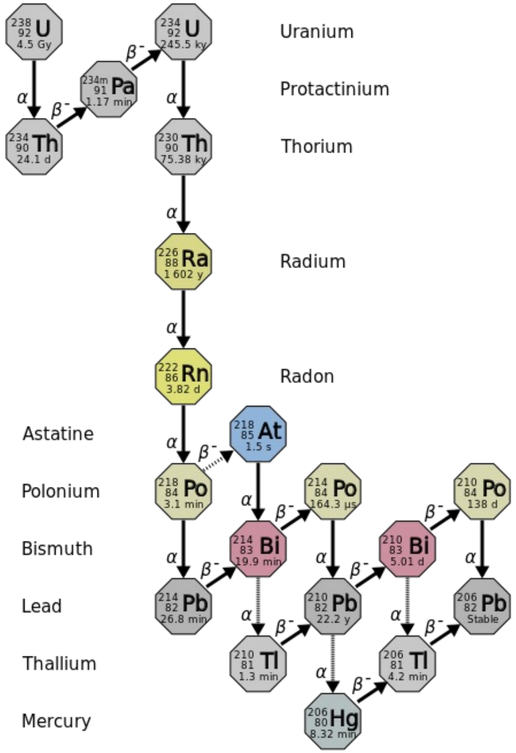

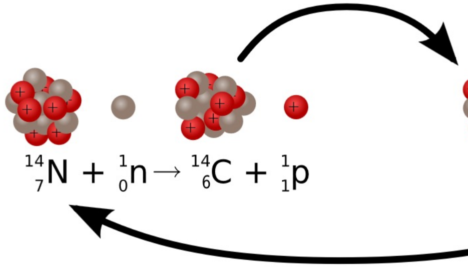

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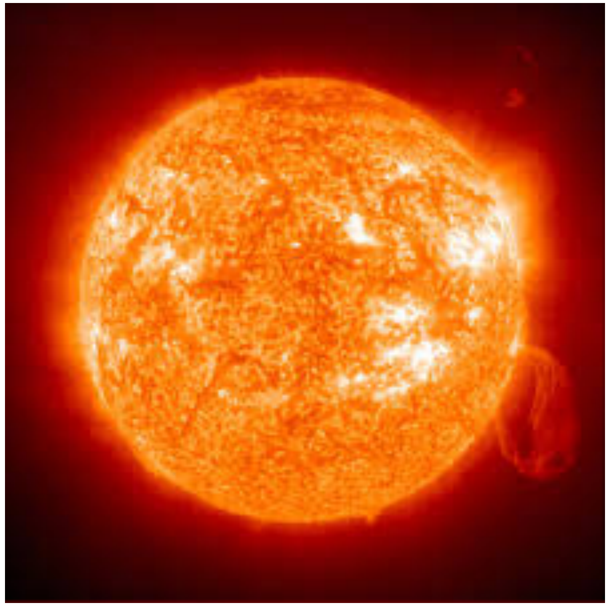

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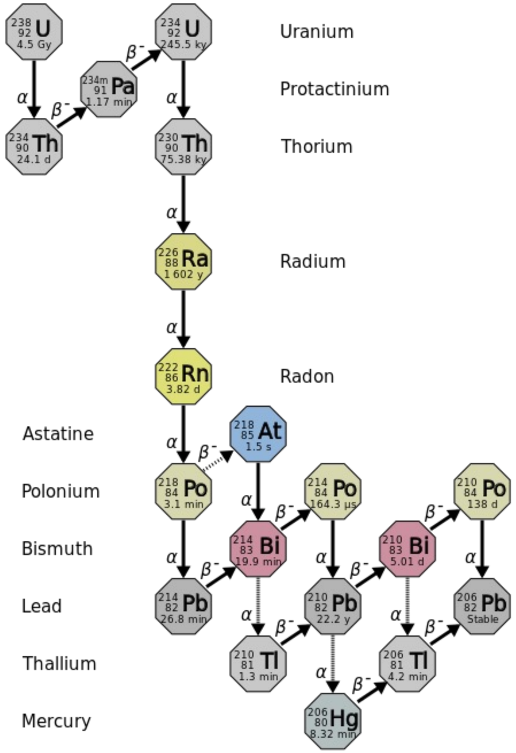

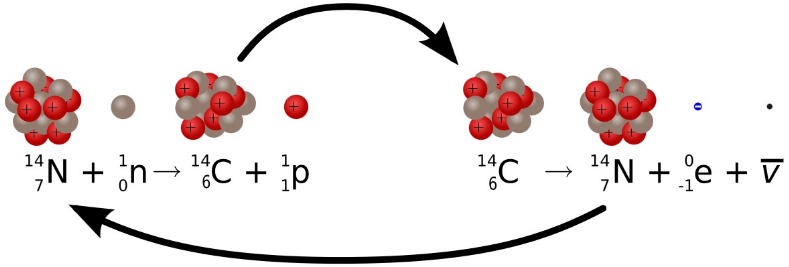

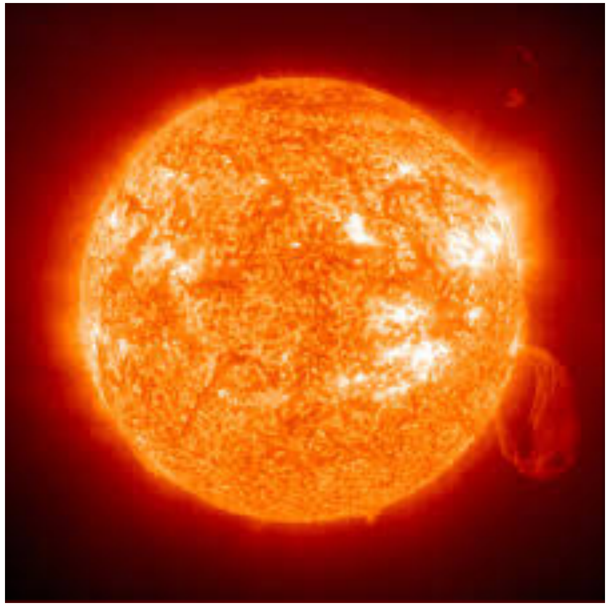

It is thanks to natural radioactivity that all the elements in the universe have been created.
You are all made of radioactive garbage!

Discovery of artificial radioactivity

Irène CURIE
(1896 – 1956) 🇫🇷
Frédéric JOLIOT
(1900 – 1958) 🇫🇷
2/2 Nobel Prize (1935)

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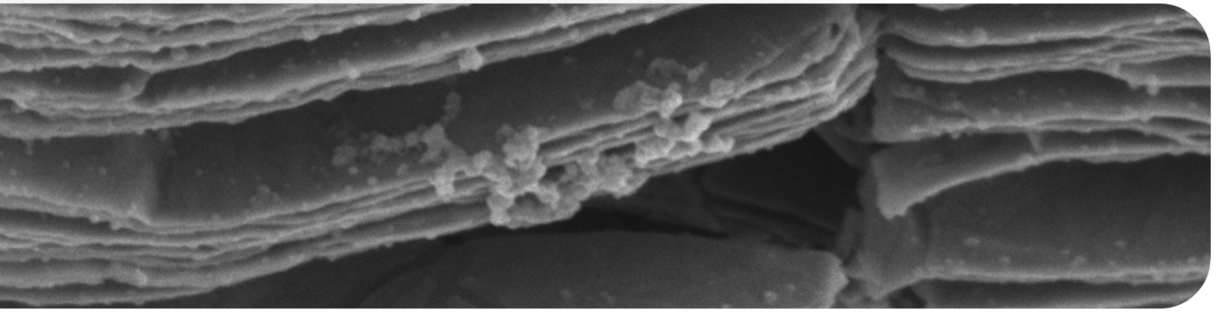

The nuclear energy

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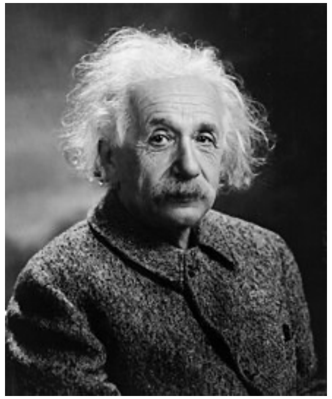
> Since radioactivity had proven that an atom could release energy, scientists sought to understand how.

Hidden energy in the atom: the key to the mystery

Why do radioactive elements emit so much energy?



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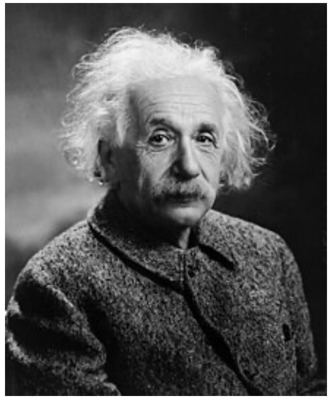

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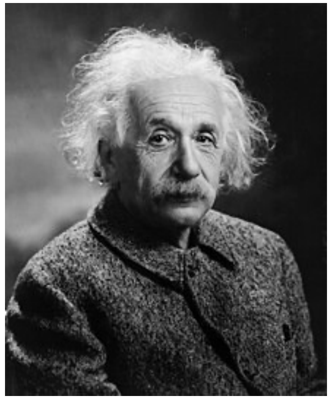

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↳ Provided the theoretical foundation that explained the discoveries of Curie and Rutherford and laid the groundwork for modern nuclear physics.

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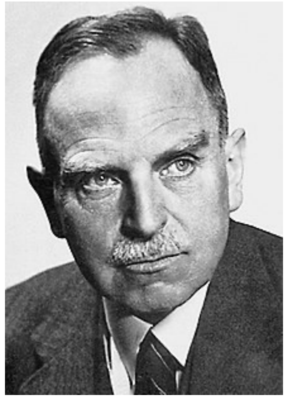
- Typically, mass defect is expressed in atomic mass units (u), and energy in MeV using:

$$1\ \mathrm{u} = \frac{1}{12} m_{^{12}C\ atoms} \overset{mc^2}{\Longrightarrow} 1\ \mathrm{u} = 931.5\ \mathrm{MeV}$$

The discovery of the fission



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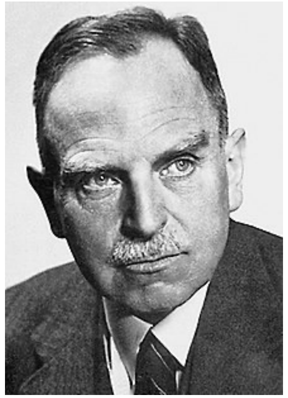

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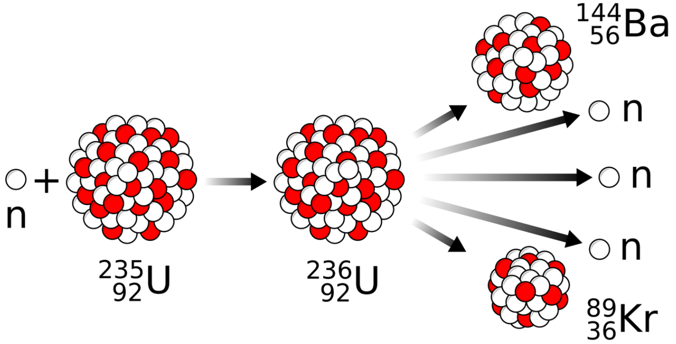

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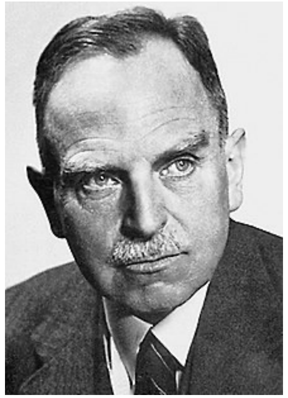

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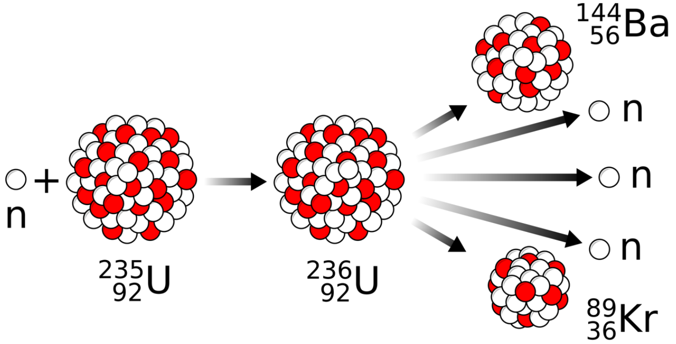

↳ Lise MEITNER and Otto FRISCH explained nuclear "fission", showing uranium splits into smaller nuclei, releasing energy and neutrons, enabling a chain reaction.

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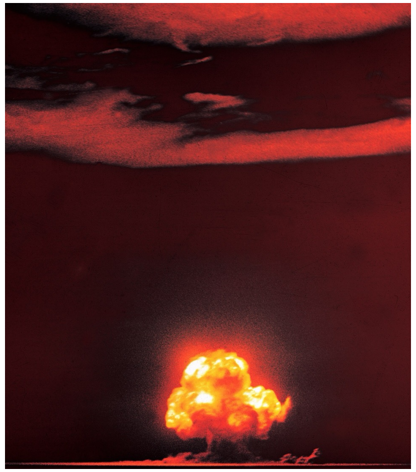

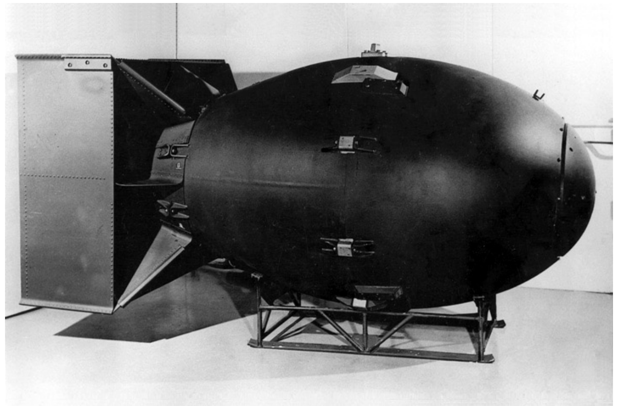

The fusion

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  - Fusion occurs when two light atomic nuclei combine to form a heavier nucleus, releasing energy due to the mass difference.
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    - ✓ *High temperature ($\sim 100 \times 10^6$ K):* Increases kinetic energy so that nuclei collide with enough force to overcome repulsion.
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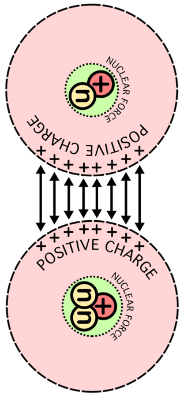

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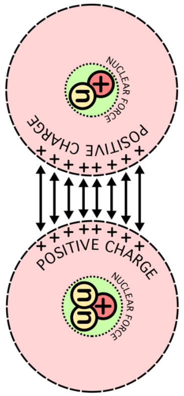

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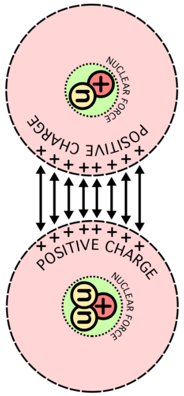

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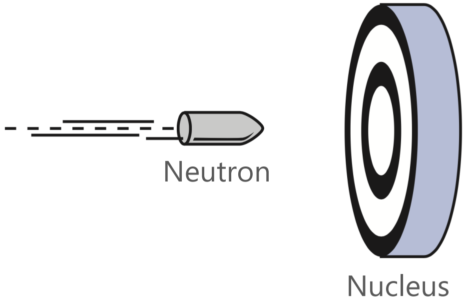
    - ✓ *Inertial Confinement (ICF):* Uses powerful lasers or particle beams to compress a small fuel pellet, triggering fusion (e.g., NIF).

➯ Fusion occurs by overcoming the Coulomb barrier, with advances in confinement bringing us closer to sustained energy production.

A.S. Eddington, *Obs.* (1920); M.L.E. Oliphant et al., *Proc. R. Soc. A.* (1934);
H.A. Bethe, *Phys. Rev.* (1939); G. Gamow, *Z. Phys.* (1928)

The cross section

Cross section the probability that a certain reaction will occur between two particles for a given set of parameters.



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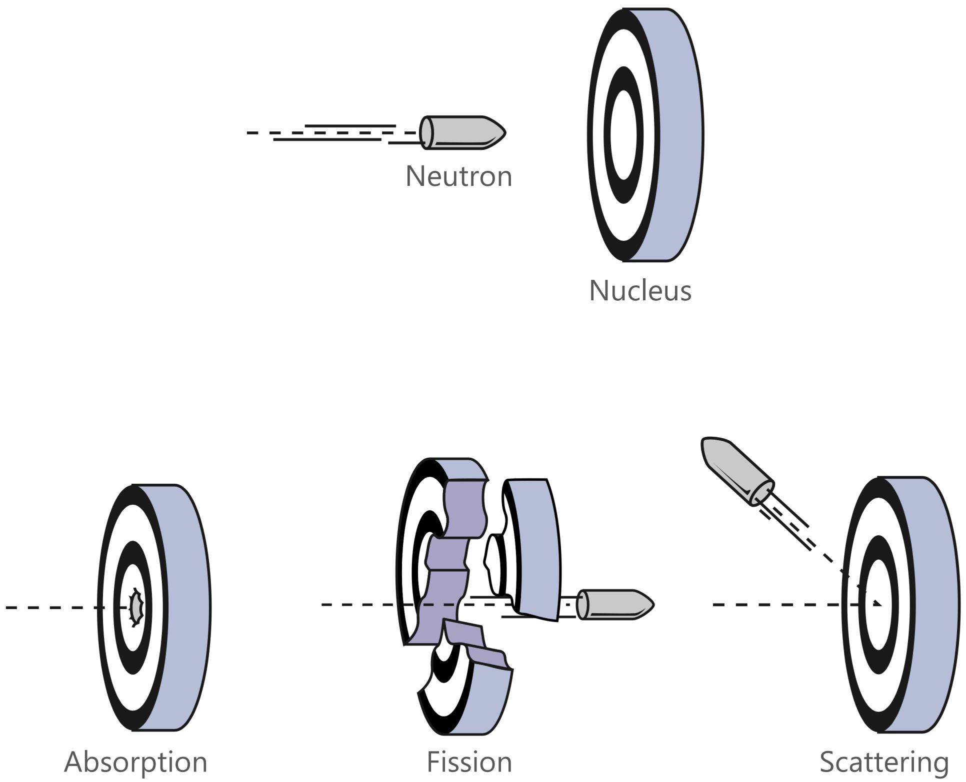

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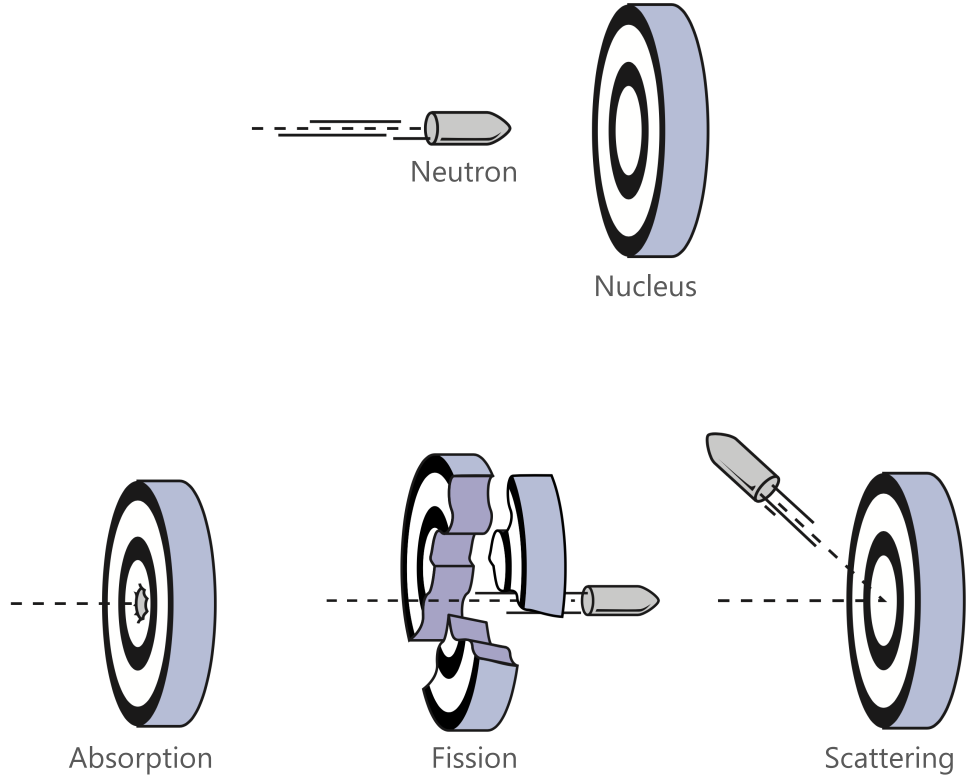

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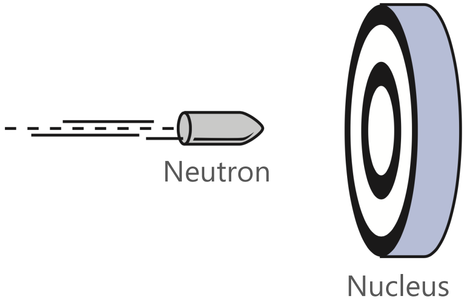

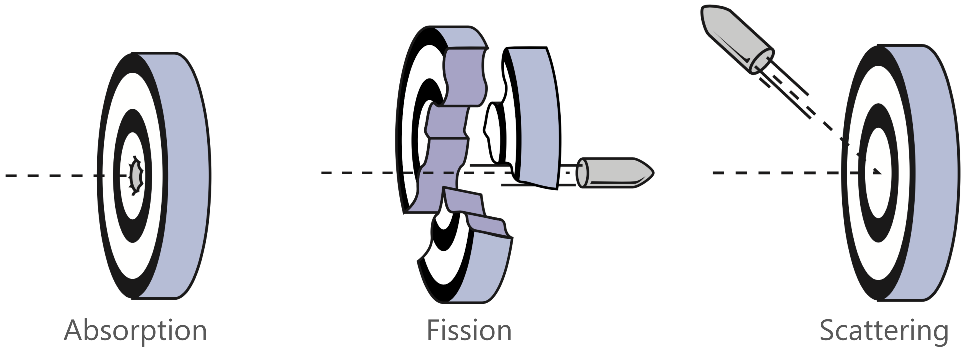

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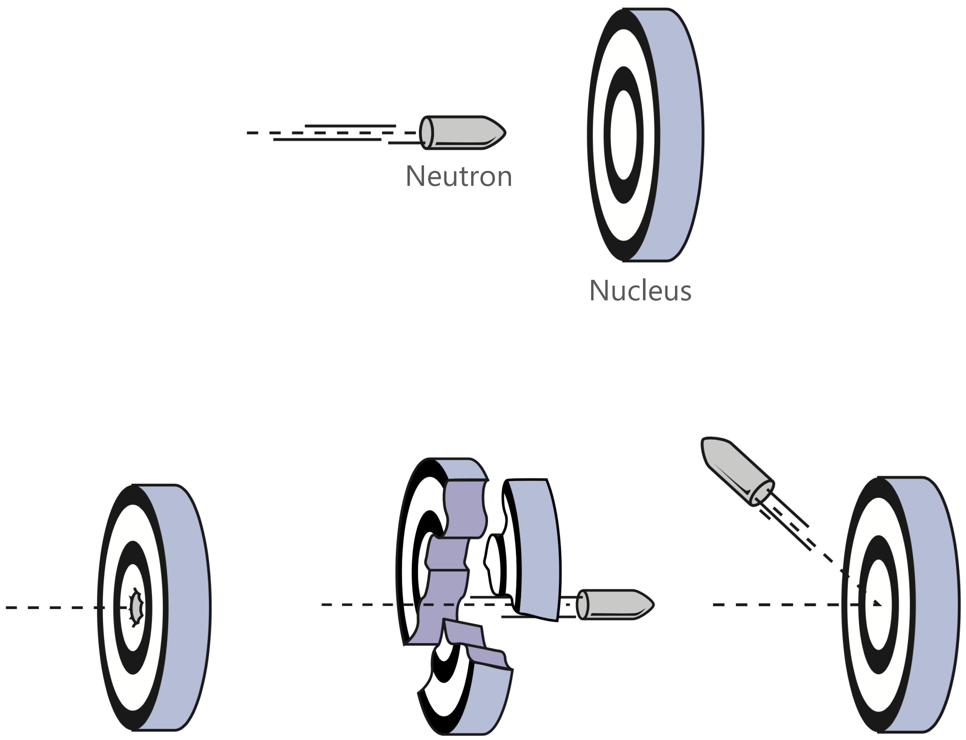

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❖ Mean free path:

- How far on average a neutron will travel before it interacts with a nucleus
  $$\bar{l}[\text{m}] = \frac{1}{\Sigma}$$

Which uranium isotope is used?

Despite its reported 26 isotopes, only $^{235}_{92}U$ is used

- **Why $^{235}_{92}U$:**
  - *Fissile:* can sustain a chain reaction with slow (thermal) neutrons.
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- *Other uranium isotopes:* very low natural abundance; not fissile or useful; some are radioactive waste.

The chain reaction

Leó SZILÁRD
(1898 – 1964)🇭🇺🇺🇸

❖ Key points

- **Definition:** A self-sustaining sequence of reactions where the products of one step initiate further reactions.
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L. Szilárd, *Patent GB440023A* (1935

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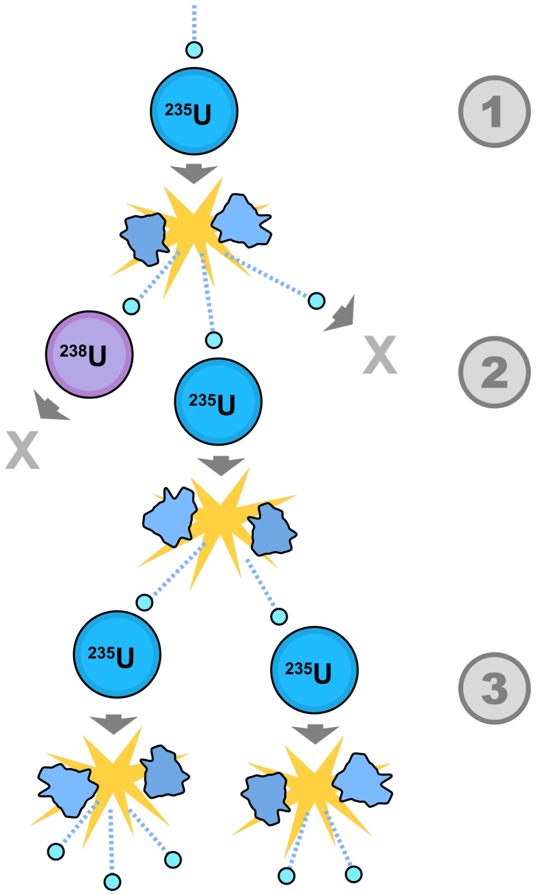

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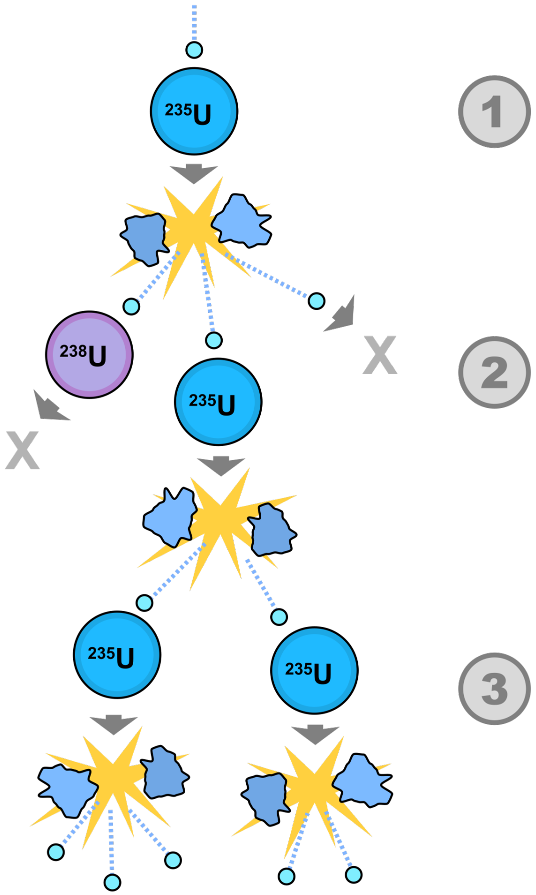

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❖ Discovery of the chain reaction

- **1933:** Leó SZILÁRD conceived the idea of a nuclear chain reaction after reading an article by Rutherford, who claimed that no such reaction could exist.
- **1939:** Szilárd, along with Fermi, conducted the first experiments on $^{235}_{92}U$, proving the possibility of a chain reaction.
- **1942:** Fermi led the first controlled chain reaction in Chicago Pile-1, the world's first nuclear reactor.

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Nuclear power plants

Cattenom (France)

- **Moderator:** A material used to slow down fast neutrons produced during nuclear fission, increasing the likelihood of further fission reactions. Common moderators include water (light or heavy), graphite, and beryllium.

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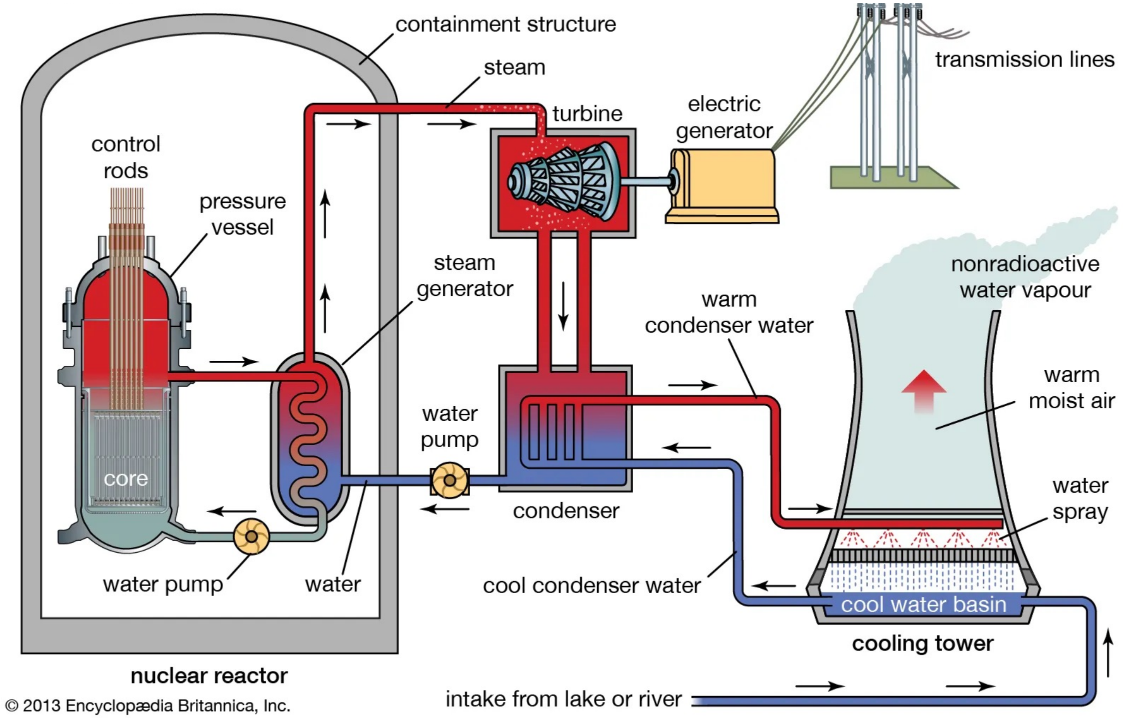
- **Fuel:** The material that undergoes nuclear fission to release energy. In most reactors, the fuel consists of enriched uranium ($^{235}_{92}U$), plutonium ($^{239}_{94}Pu$), or mixed oxide (MOX) fuel

Nuclear power plants

EPR (European Pressurized Reactor)



- **Main reactor types:**
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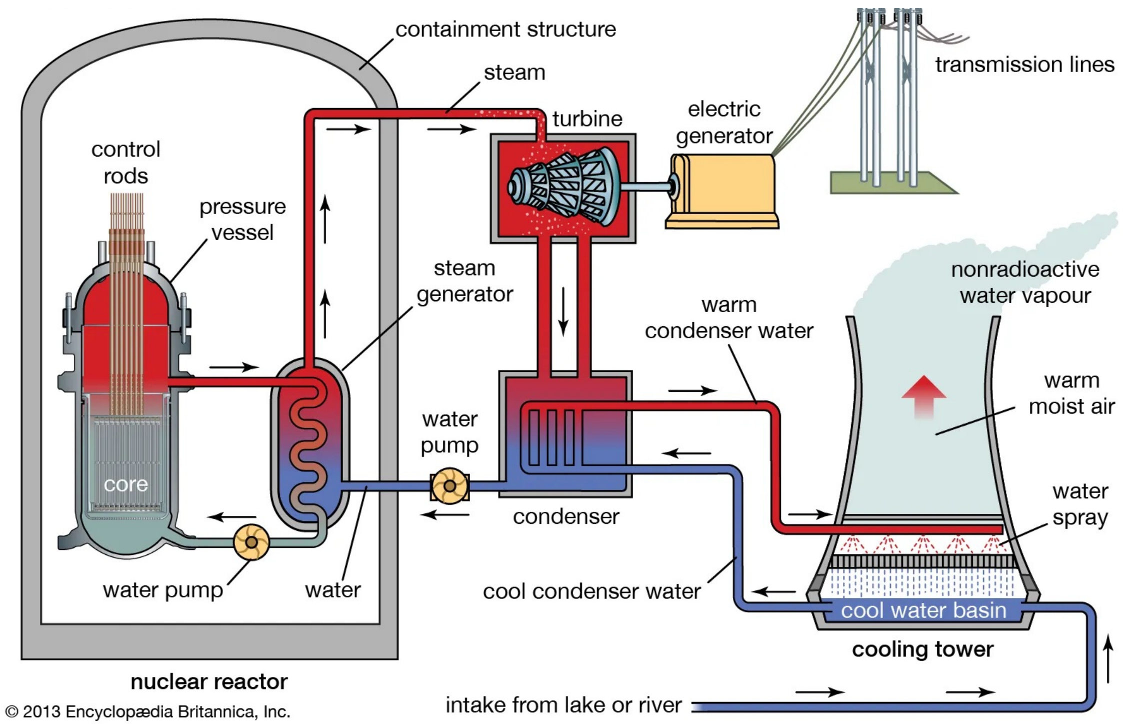

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  - ***CANDU (Heavy Water Reactor)* –** *Moderator:* heavy water; *Coolant:* heavy water; *Fuel:* enriched uranium (~3-5% $^{235}_{92}U$).
  - **FNR (Fast Neutron Reactor) –** *Moderator:* none; *Coolant:* sodium or lead; *Fuel:* mixed oxide (MOX) or depleted uranium (<0.3% $^{235}_{92}U$).
  - ***MSR (Molten Salt Reactor)* –** *Moderator:* graphite; *Coolant:* molten salt; *Fuel:* uranium or thorium dissolved in molten salt.
  - **RBMK (Reaktor Bolshoy Moshchnosti Kanalny) –** *Moderator:* graphite; *Coolant:* light water; *Fuel:* low-enriched uranium (~2% $^{235}_{92}U$); used in Chernobyl.

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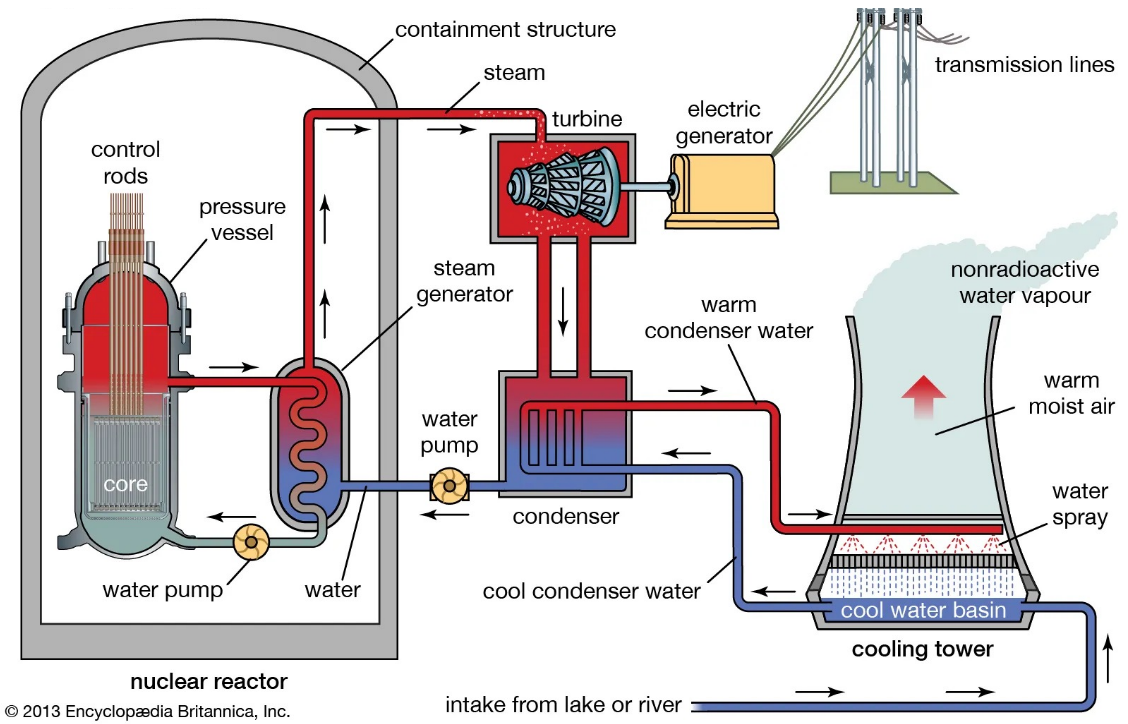

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- **Nuclear reactor generations**
  - *1st Gen (1950-1970)* – Early commercial reactors, low safety.
  - *2nd Gen (1970-2000)* – Standardized, used in Chernobyl and Fukushima.
  - *3rd Gen (2000-Present)* – Passive safety, longer lifespan (EPR, AP1000).
  - *4th Gen (Future)* – Intrinsic safety, reduced waste (SFR, MSR, HTGR).

Thanks for your listening!

If you need further information:

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LABORATOIRE D'ÉTUDE DES MICROSTRUCTURES ET DE MÉCANIQUE DES MATÉRIAUX

UNIVERSITÉ DE LORRAINE

enim École Nationale d'Ingénieurs de Metz