Nobel prizes in nuclear and reactor physics

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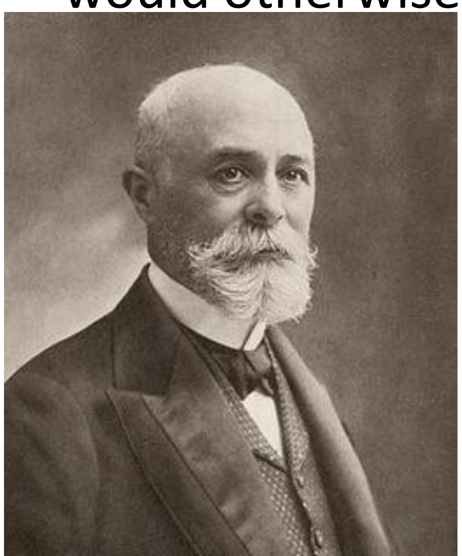
Nuclear physics in everyday life

- Electricity: production in nuclear power plants
- Sterilization by the application of ionizing radiation
- Medical examinations: X-ray checks, PET scans, MRI scans, CT examinations
- Therapy of tumors by use of particle accelerators or radioactive sources

Discovery of radioactive decay

- Radioactivity was rediscovered in 1896 by the French scientist Henri Becquerel.
- Further research by Becquerel, Rutherford, Paul Villard, Pierre Curie, Marie Curie, and others discovered that different types of decay can occur, producing very different types of radiation. Rutherford realized that they all occur in accordance with the same mathematical exponential formula.
- The early researchers also discovered that many other chemical elements besides uranium have radioactive isotopes. Pierre Curie and Marie Curie isolated a new element polonium and to separate a new element radium from barium. The two elements' chemical similarity would otherwise have made them difficult to distinguish.



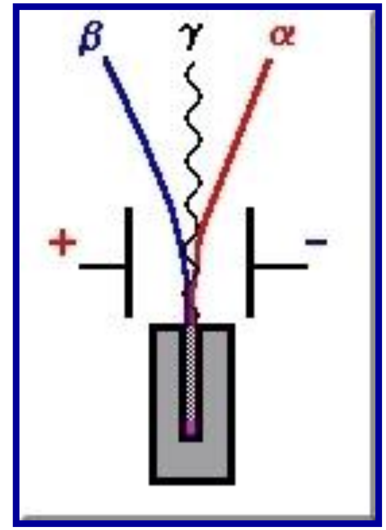
Henry Becquerel

Nobel prize in physics in 1903

Pierre Curie
Marie Curie

Nobel prize in physics in 1903

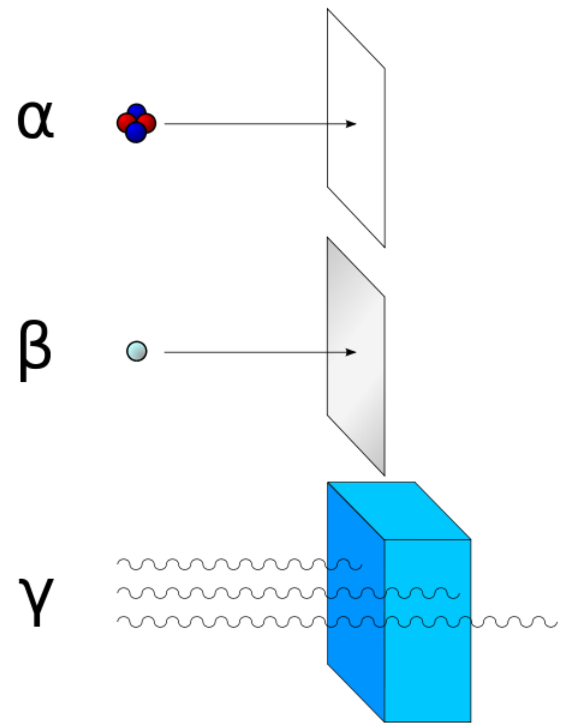
Types of radioactive decay



Einstein: $E = m \cdot c^2$. Since $m \geq 0$, the total energy $E \geq 0$.

<u>Radioactive decays:</u>

- α – particles: $^{4}_{2}\mathrm{He}$ nuclei
- β – particles: high energy electrons
- γ - radiation: electromagnetic (photons)



Atomic nuclei transform into one another

conserved quantities

- energy (taking into account $E = mc^2$)
- nucleon number (A)
- electric charge (nucleus: $+Ze$, electron: $-e$)

Beta Particles

Beta particles are subatomic particles ejected from the nucleus of some radioactive atoms. They are equivalent to electrons. The difference is that beta particles originate in the nucleus and electrons originate outside the nucleus.

There are many beta emitters:

- tritium
- cobalt-60
- strontium-90
- technetium-99
- iodine-129
- iodine-131
- cesium-137

Gamma Rays

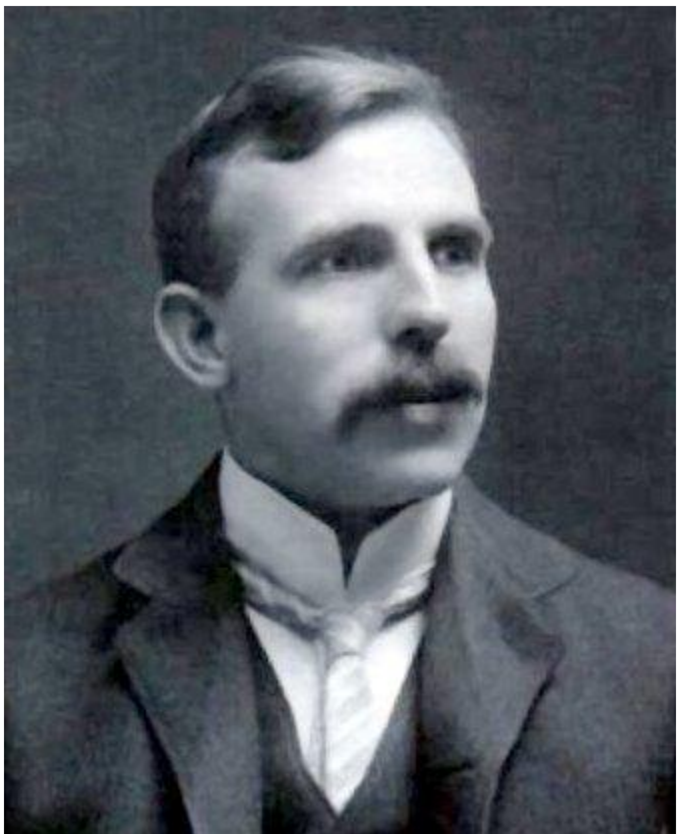
A gamma ray is a packet of electromagnetic energy--a photon. Gamma photons are the most energetic photons in the electromagnetic spectrum. Gamma rays (gamma photons) are emitted from the nucleus of some unstable (radioactive) atoms.

Gamma emitting radionuclides are the most widely used radiation sources. The three radionuclides by far most useful are:

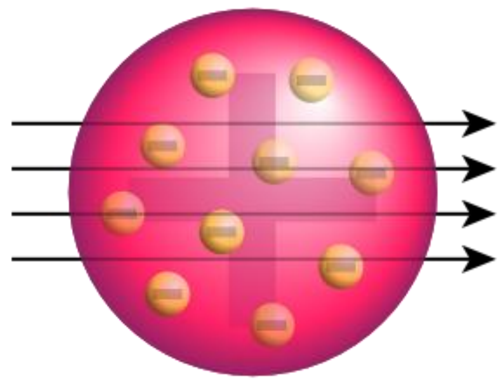
- cobalt-60,
- cesium-137,
- technetium-99 m.

Discovery of the atomic nucleus

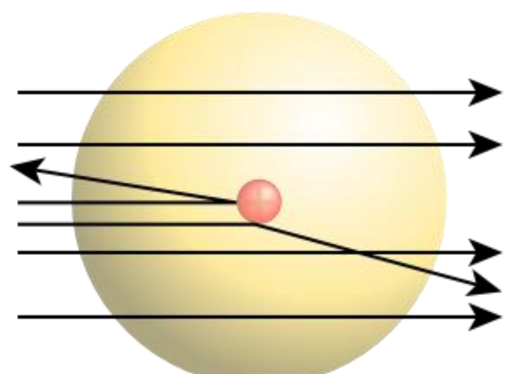
In 1902 Ernest Rutherford showed that radioactivity as a spontaneous event emitting an alpha or beta particle from the nucleus created a different element. Ernest Rutherford proposed the atomic structure with the massive nucleus in 1911.



Nobel prize in chemistry in 1908



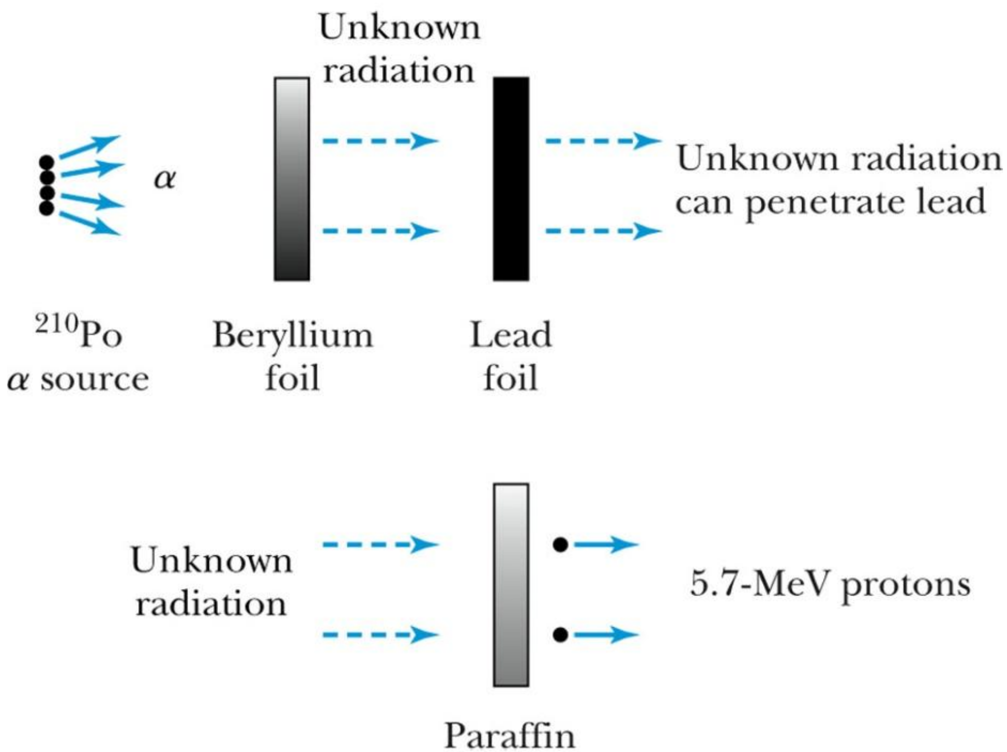
Expected results: alpha particles passing through the plum pudding model of the atom undisturbed.



Observed results: a small portion of the particles were deflected, indicating a small, concentrated charge.

Discovery of the neutron

In 1930 the German physicists Bothe and Becker used a radioactive polonium source that emitted α particles. When these α particles bombarded beryllium, the radiation penetrated several centimeters of lead.



Discovery of the neutron

In 1932 James Chadwick discovered the neutron. Also in 1932 Cockcroft and Walton produced nuclear transformations by bombarding atoms with accelerated protons

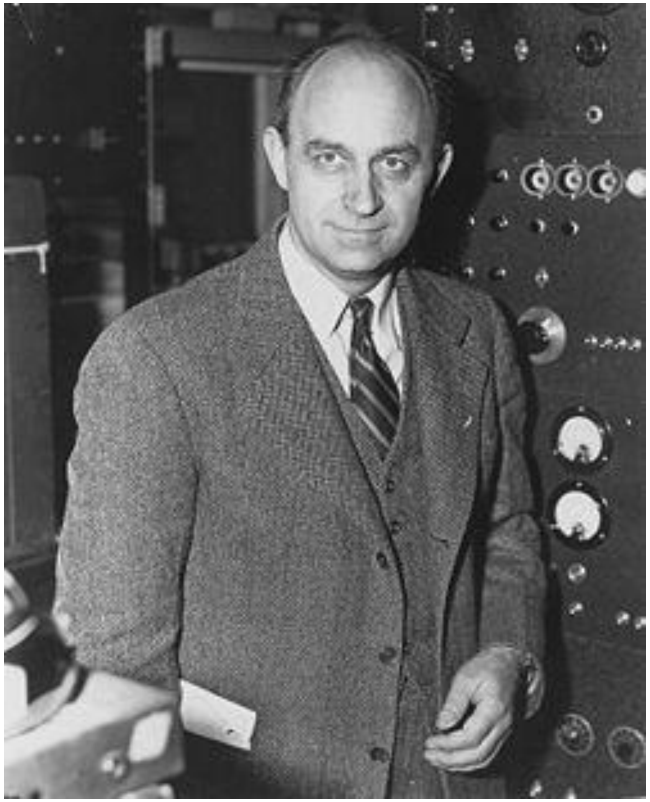
1934 Irene Curie and Frederic Joliot found that some such transformations created artificial radionuclides.

James Chadwick

Nobel prize in physics in 1935

Nuclear reactions

In 1935 Enrico Fermi found that a much greater variety of artificial radionuclides could be formed when neutrons were used instead of protons.



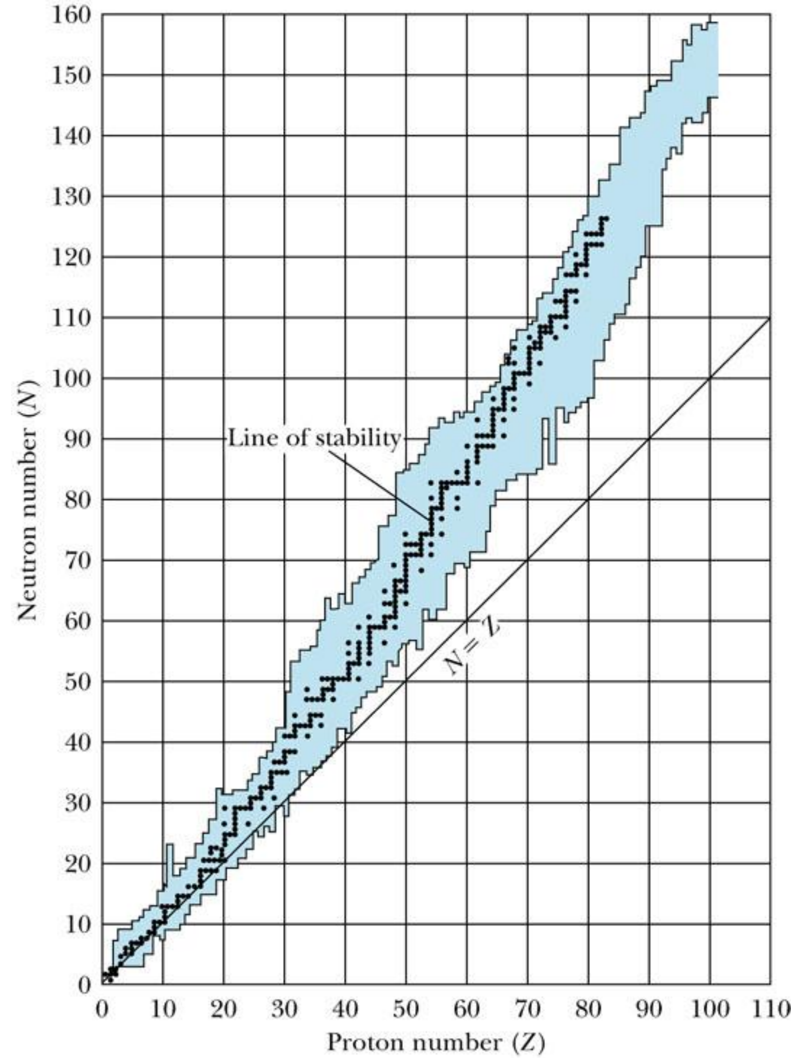
Enrico Fermi

Nobel prize in physics in 1938

Nuclear Stability

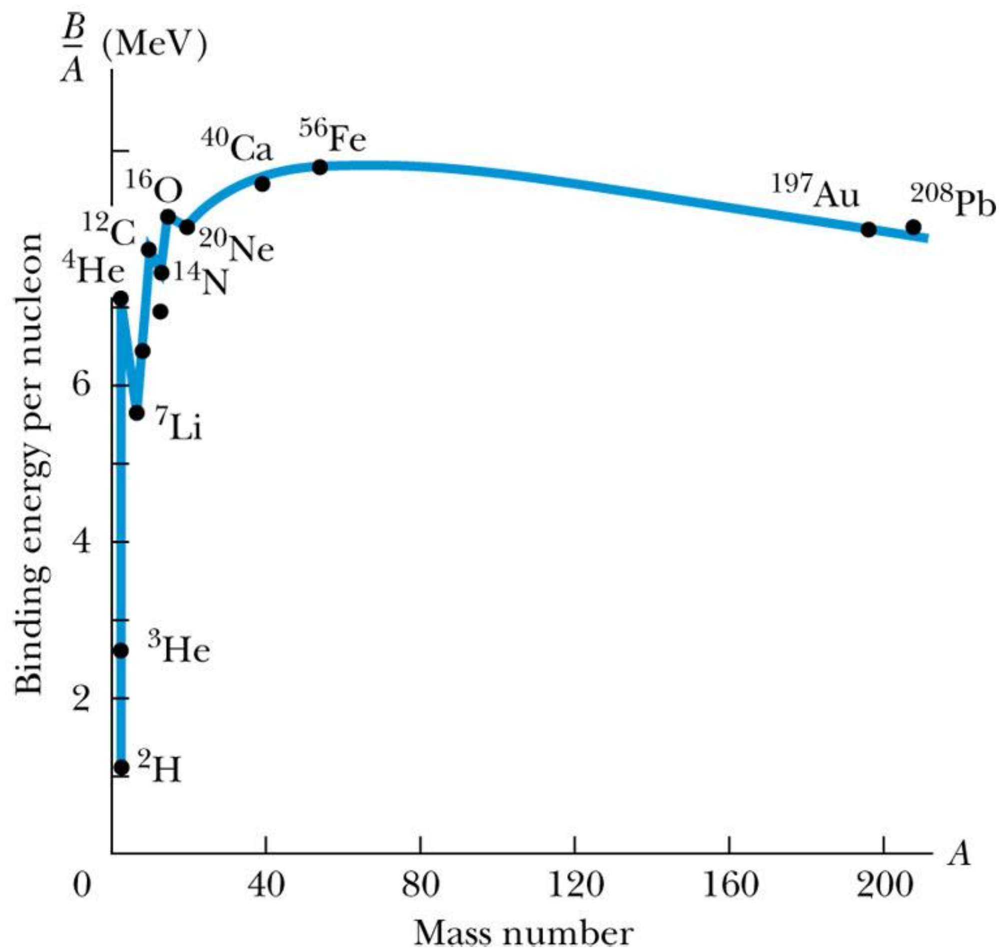
- The binding energy of a nucleus against dissociation into any other possible combination of nucleons.
- Proton (or neutron) *separation energy*:
  - The energy required to remove one proton (or neutron) from a nuclide.
- All stable and unstable nuclei that are long-lived enough to be observed.
- The line representing the stable nuclides is the **line of stability**.
- It appears that for $A \leq 40$, nature prefers the number of protons and neutrons in the nucleus to be about the same $Z \approx N$.

  However, for $A \geq 40$, there is a decided preference for $N > Z$ because the nuclear force is independent of whether the particles are *nn*, *np*, or *pp*.
- As the number of protons increases, the Coulomb force between all the protons becomes stronger until it eventually affects the binding significantly.



Binding Energy Per Nucleon

- Use this to compare the relative
  stability of different nuclides.
- It peaks near A = 56.
- The curve increases rapidly, demonstrating the saturation effect of nuclear force.



Radioactive Nuclides

- The unstable nuclei found in nature exhibit natural radioactivity.

Table 12.2 Some Naturally Occurring Radioactive Nuclides

Nuclide	$t_{1/2}$ (y)	Natural Abundance
$^{40}_{19}K$	1.28×10^{9}	0.01%
$^{87}_{37}Rb$	4.8×10^{10}	27.8%
$^{113}_{48}Cd$	9×10^{15}	12.2%
$^{115}_{49}In$	4.4×10^{14}	95.7%
$^{128}_{52}Te$	7.7×10^{24}	31.7%
$^{130}_{52}Te$	2.7×10^{21}	33.8%
$^{138}_{57}La$	1.1×10^{11}	0.09%
$^{144}_{60}Nd$	2.3×10^{15}	23.8%
$^{147}_{62}Sm$	1.1×10^{11}	15.0%
$^{148}_{62}Sm$	7×10^{15}	11.3%

Nuclear reactions

Importance: most of our knowledge on the atomic nuclei is based on the investigation of nuclear reactions

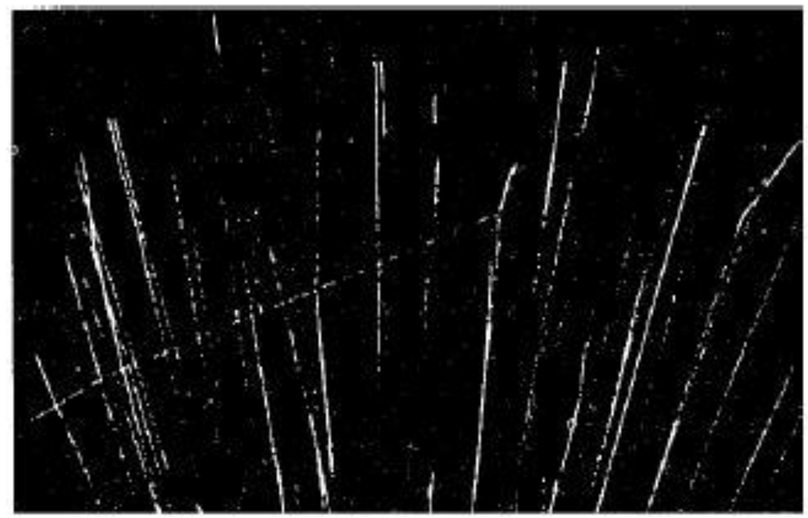
First artificially induced (observed)nuclear reaction:
E. Rutherford (1919)

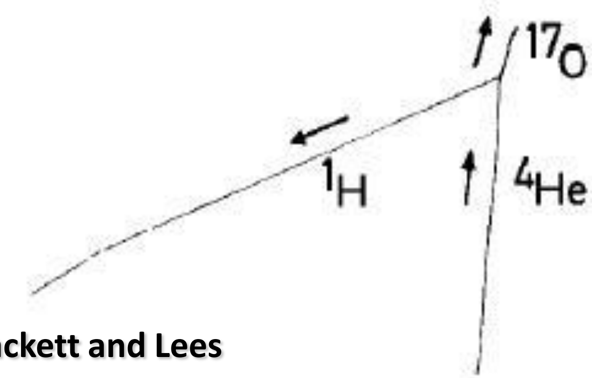
Observation: in a steam chamber

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

α-particle, from radium

Nitrogen, filling gas of the steam chamber





Blackett and Lees

Two ways to release nuclear energy

Fusion
(big nuclei from small ones)

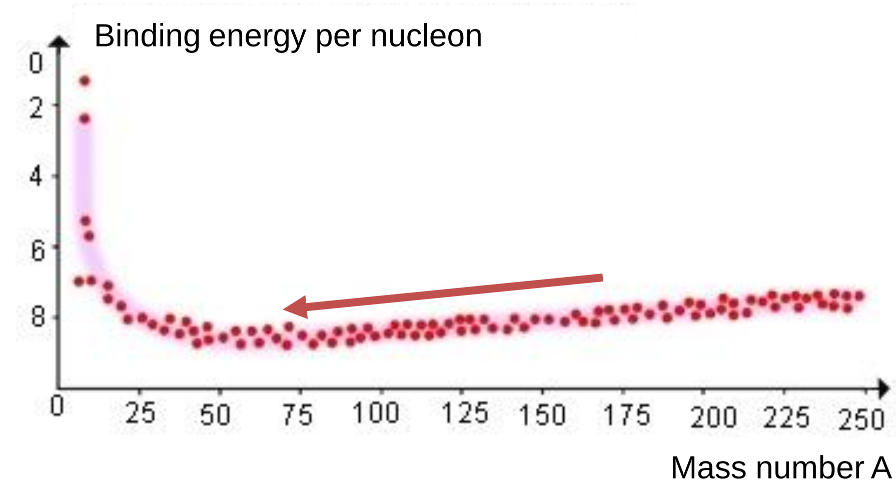
Example

$^{2}H + ^{3}H \longrightarrow ^{4}He + n$

(Q = 17,6 MeV)

Fission
(small nuclei from big ones)

Binding energy per nucleon vs. mass number



Fusion:
- **large energy gain/nucleon (~ 2 … 5 MeV/nucleon)**
- **small number of nucleons (~ 2...5)**

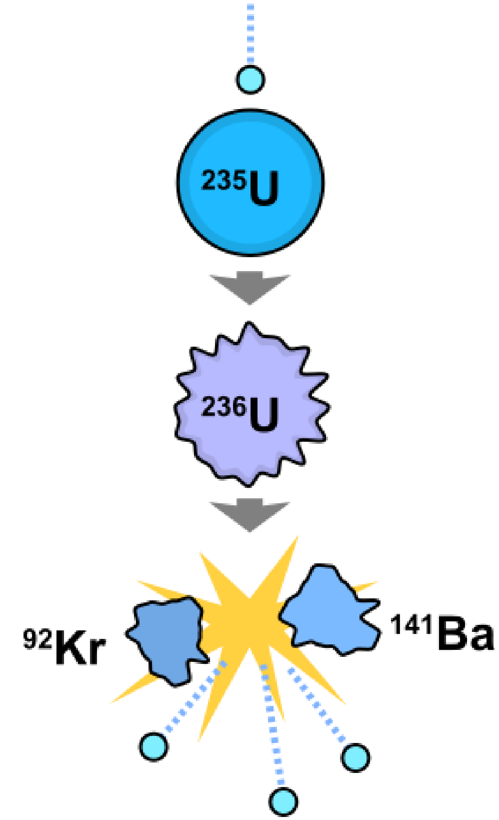
Total of ~ 2 – 18 MeV

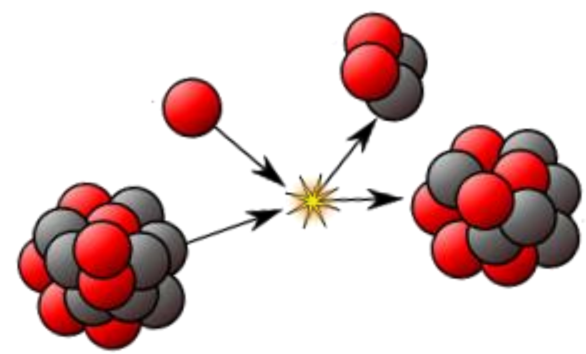
Fission:
- **small energy gain/nucleon (~0,85 MeV/nucleon)**
- **very many nucleons (~235)**

Total of ~ 200 MeV

Nuclear fission

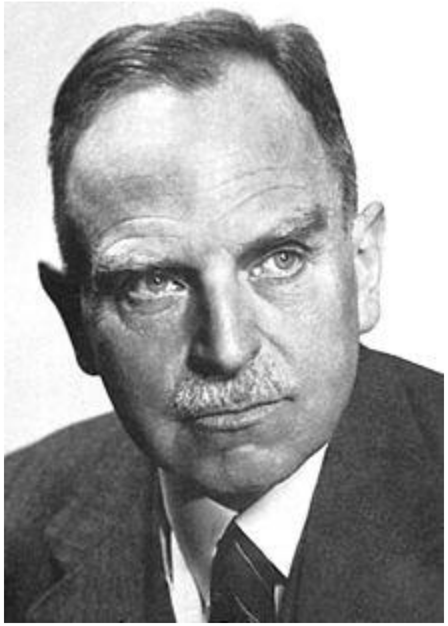
Nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of a particle splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays), and releases a very large amount of energy even by the energetic standards of radioactive decay.





Discovery of nuclear fission

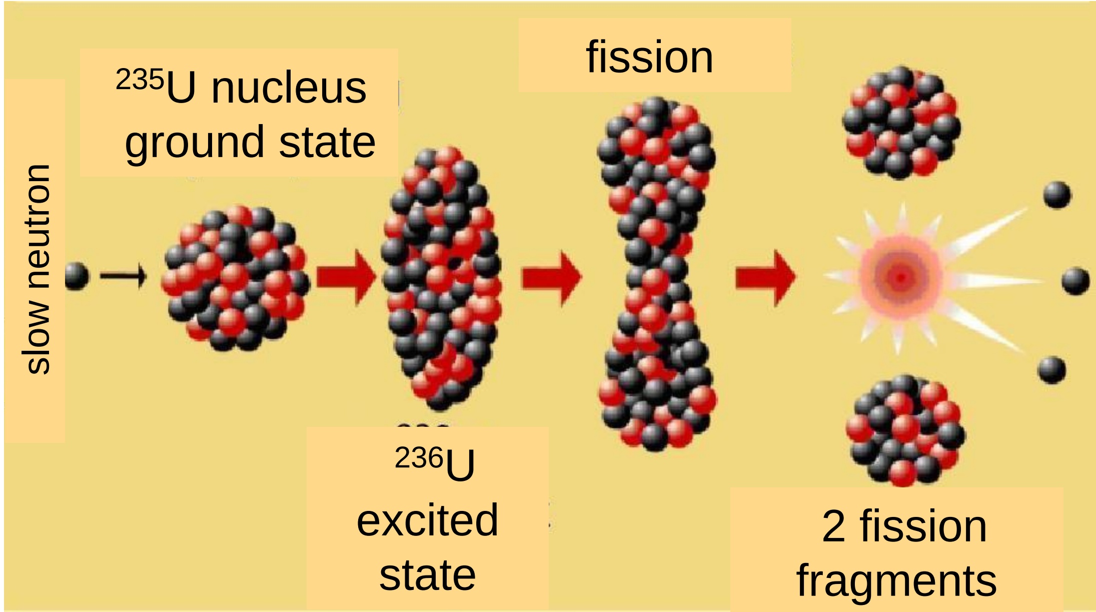
Nuclear fission of heavy elements was discovered on December 17, 1938 by Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch. Frisch named the process by analogy with biological fission of living cells. It is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). In order for fission to produce energy, the total binding energy of the resulting elements must be greater than that of the starting element.

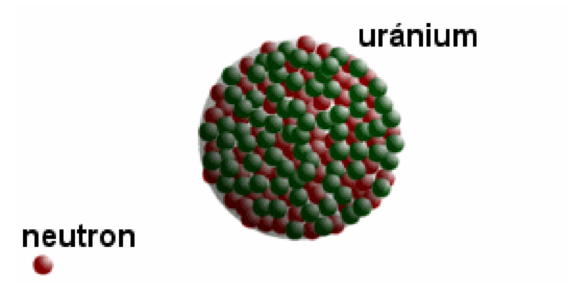


Otto Hahn

Nobel prize in chemistry in 1944

The process of nuclear fission





Neutron induced fission

1) The nucleus gets to an excited state (eg. when capturing a neutron)

2) The shape deformates

3) Splits into two parts, along with the emission of a few neutrons

Some very heavy nuclei may undergo spontaneous fission as well, for which there is no need of excitation. In this case step #1 is skipped

Nuclear Fission, Chain Reaction and Nuclear Reactor

Neutron interaction with atoms of heavy nuclei such as uranium-235 leads to a 'split' with release of energy

$^{235}U + n \rightarrow [^{236}U] \rightarrow {}^{A}X + {}^{B}Y$ + 2 to 3 n + Energy

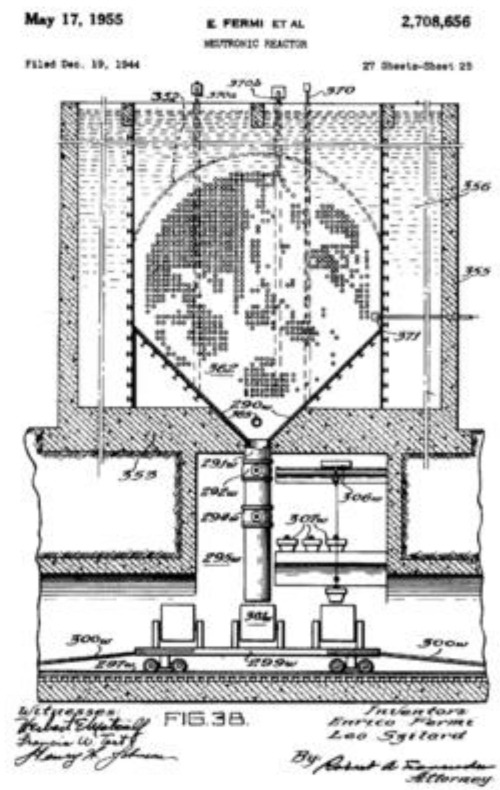
- Nuclear Fission Reaction – ***fissile element + thermal neutron***
- Neutrons released further interact with fissile element ➔ to chain (fission) reaction with energy release
- The energy released is huge! Million times larger than that released in fire
- Therefore, a bomb could also be made --- nuclear weapons
- Self sustained controlled chain reaction would lead to a steady state operation → Device → ***Nuclear Reactor***

Discovery of the chain reaction

- The concept of a nuclear chain reaction was first hypothesized by Hungarian scientist Leó Szilárd in 1933.
- After nuclear fission was discovered by Meitner, Hahn and Strassman in 1938, Szilárd and Enrico Fermi in 1939 searched for, and discovered, neutron multiplication in uranium, proving that a nuclear chain reaction by this mechanism was indeed possible

Leo Szilárd

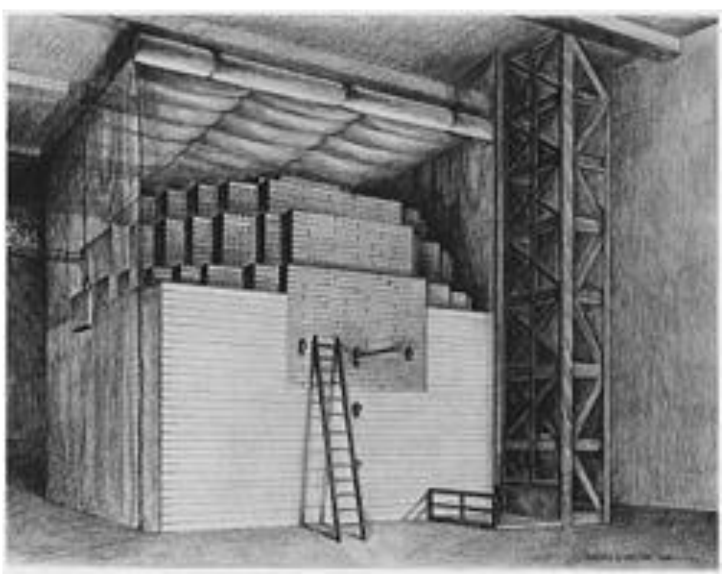
Inventor of
nuclear
chain reaction



Realization of the chain reaction

Enrico Fermi and Leo Szilárd created the first artificial self-sustaining nuclear chain reaction, called Chicago Pile-1 (CP-1), in a racquets court below the bleachers of Stagg Field at the University of Chicago on December 2, 1942.

This was part of the Manhattan Project.



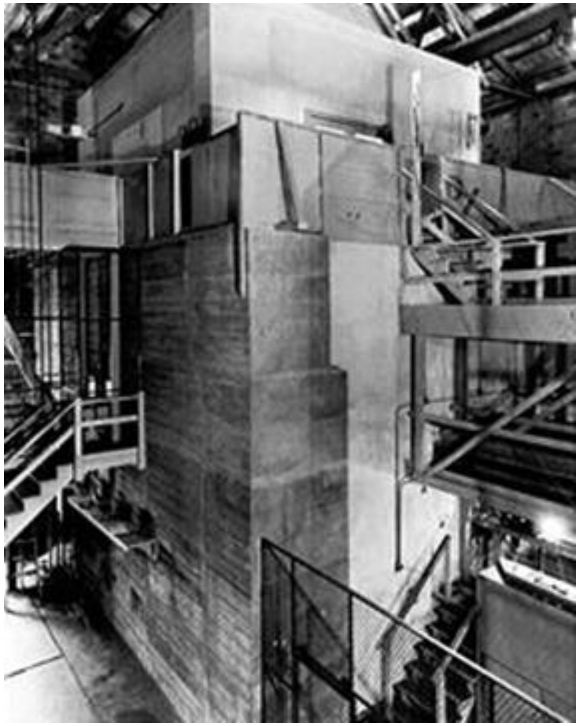
Chain reaction for production of fissile material

This work became part of the Manhattan Project, which built large reactors at the Hanford Site to breed plutonium for use in the first nuclear weapons.

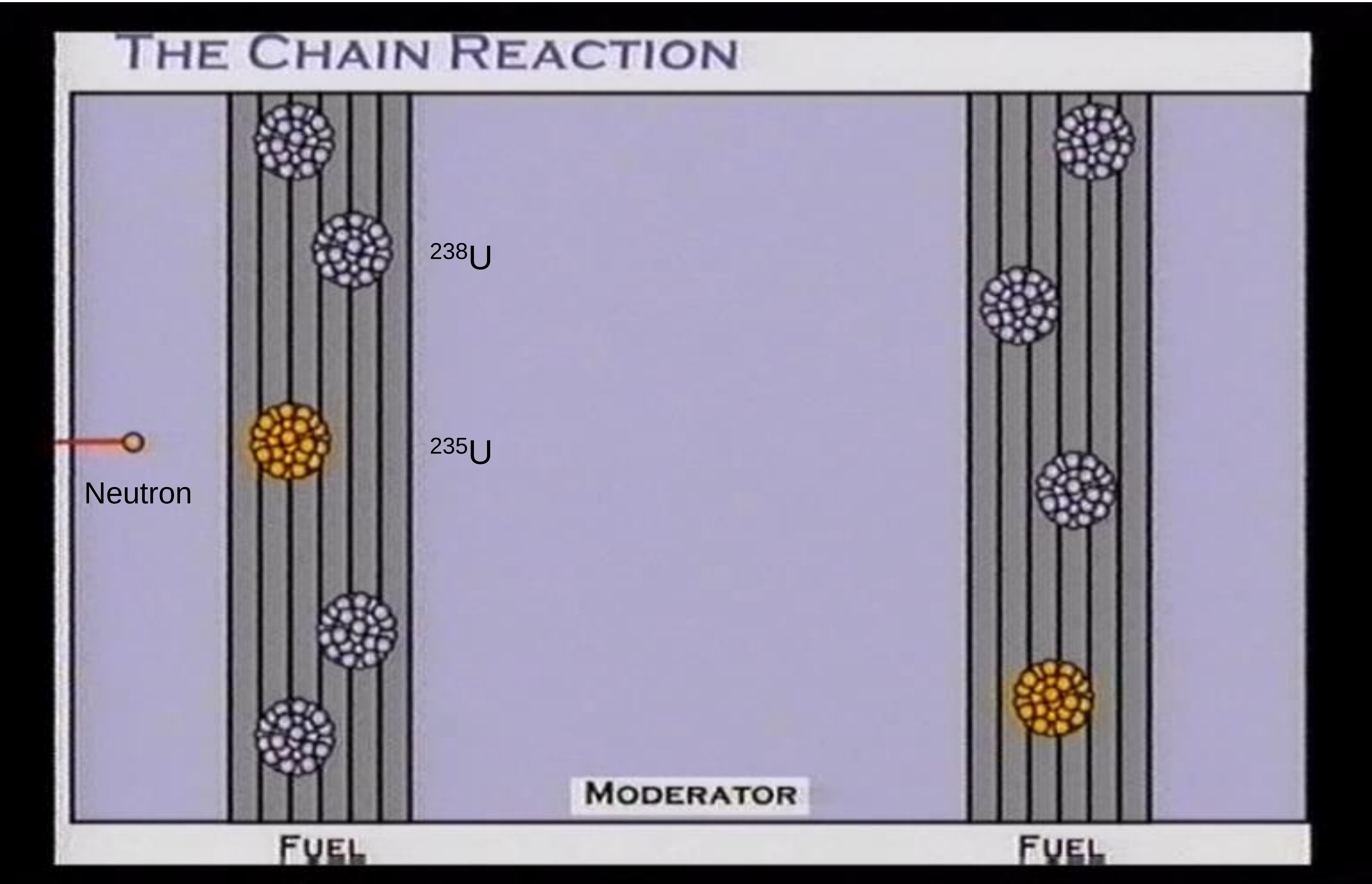
The reactors were partly designed by Eugene Wigner

Eugene Wigner

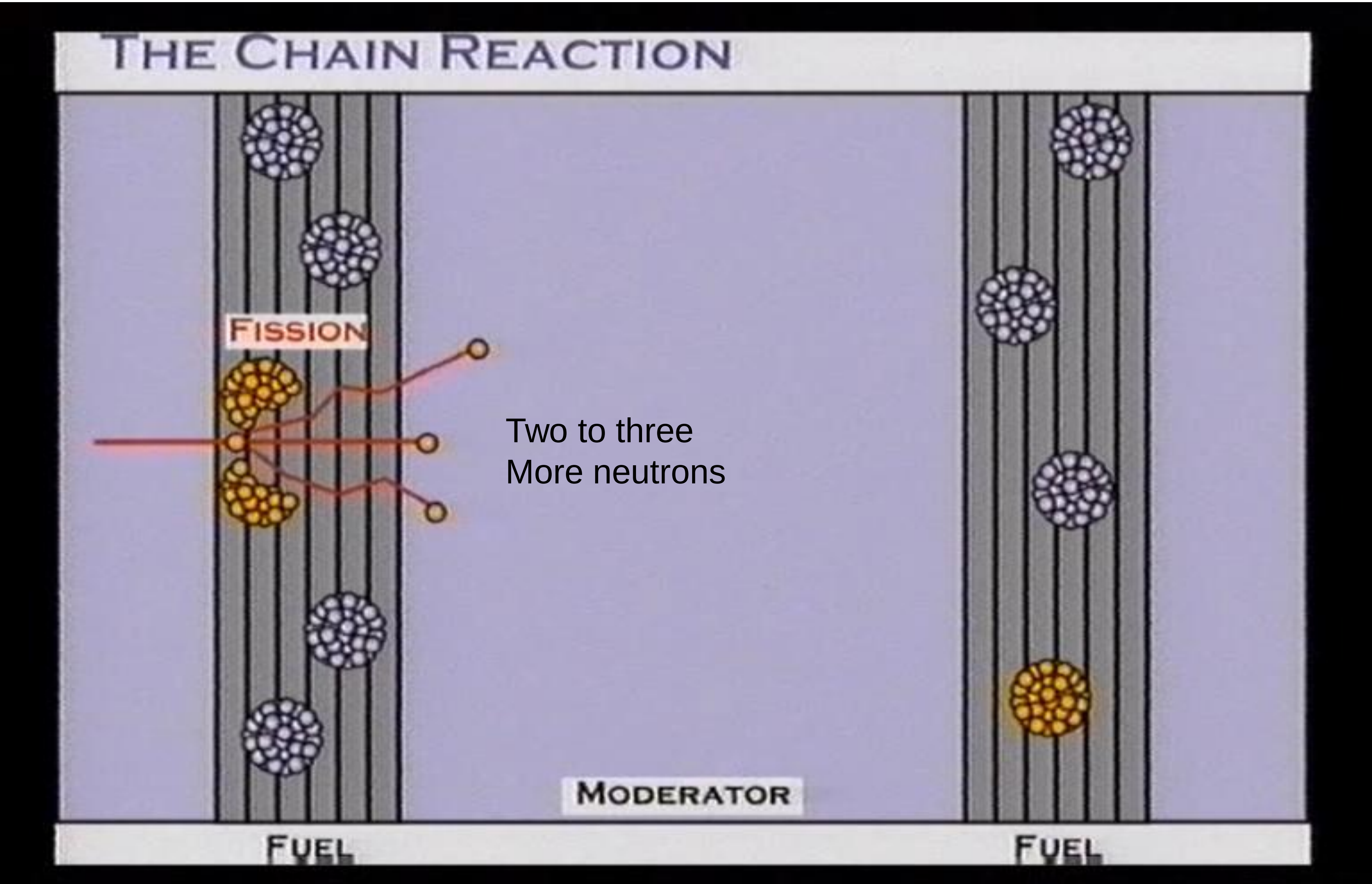
Nobel prize in physics in 1963



Fission: The Chain Reaction



Fission: The Chain Reaction



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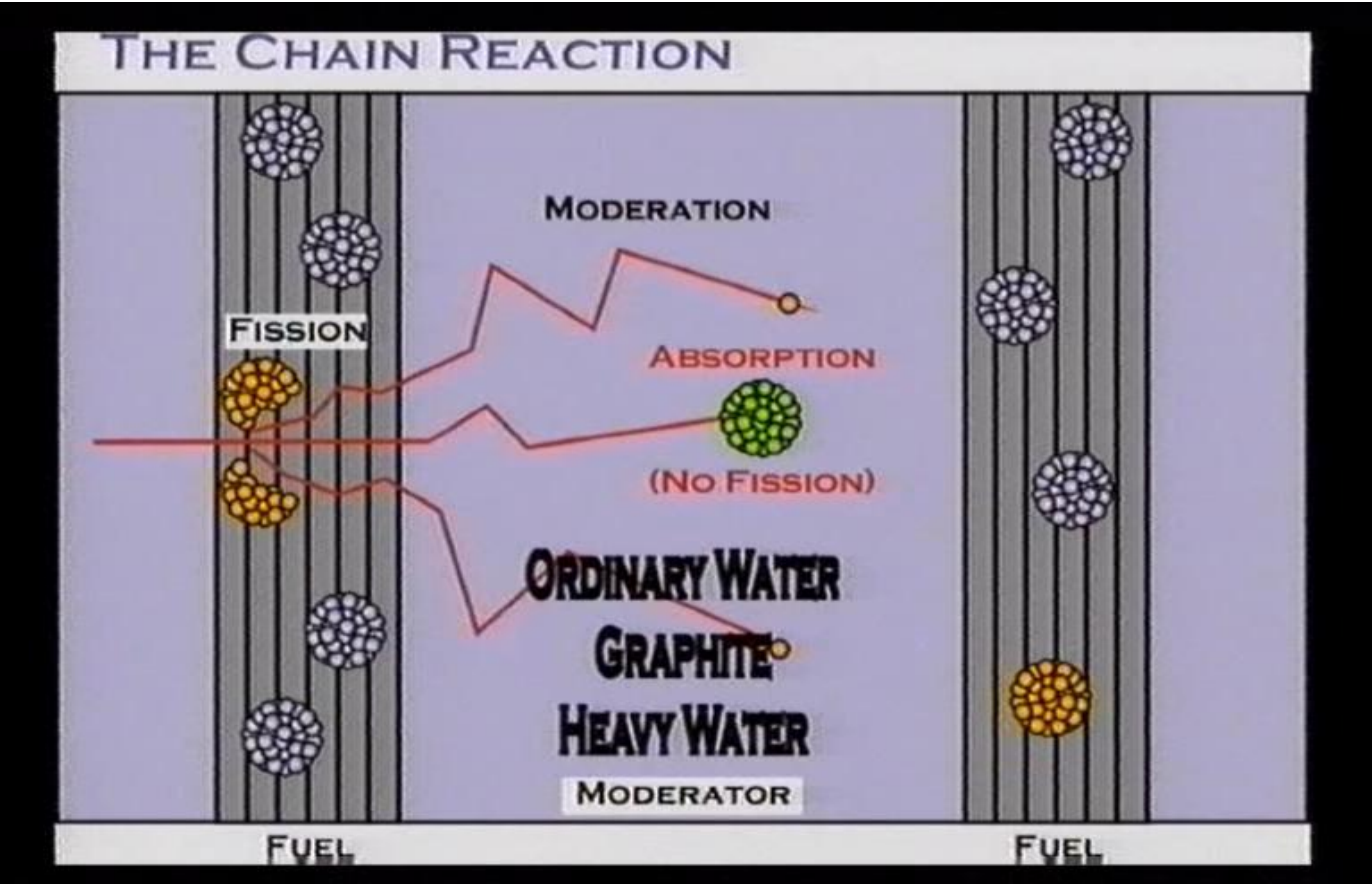
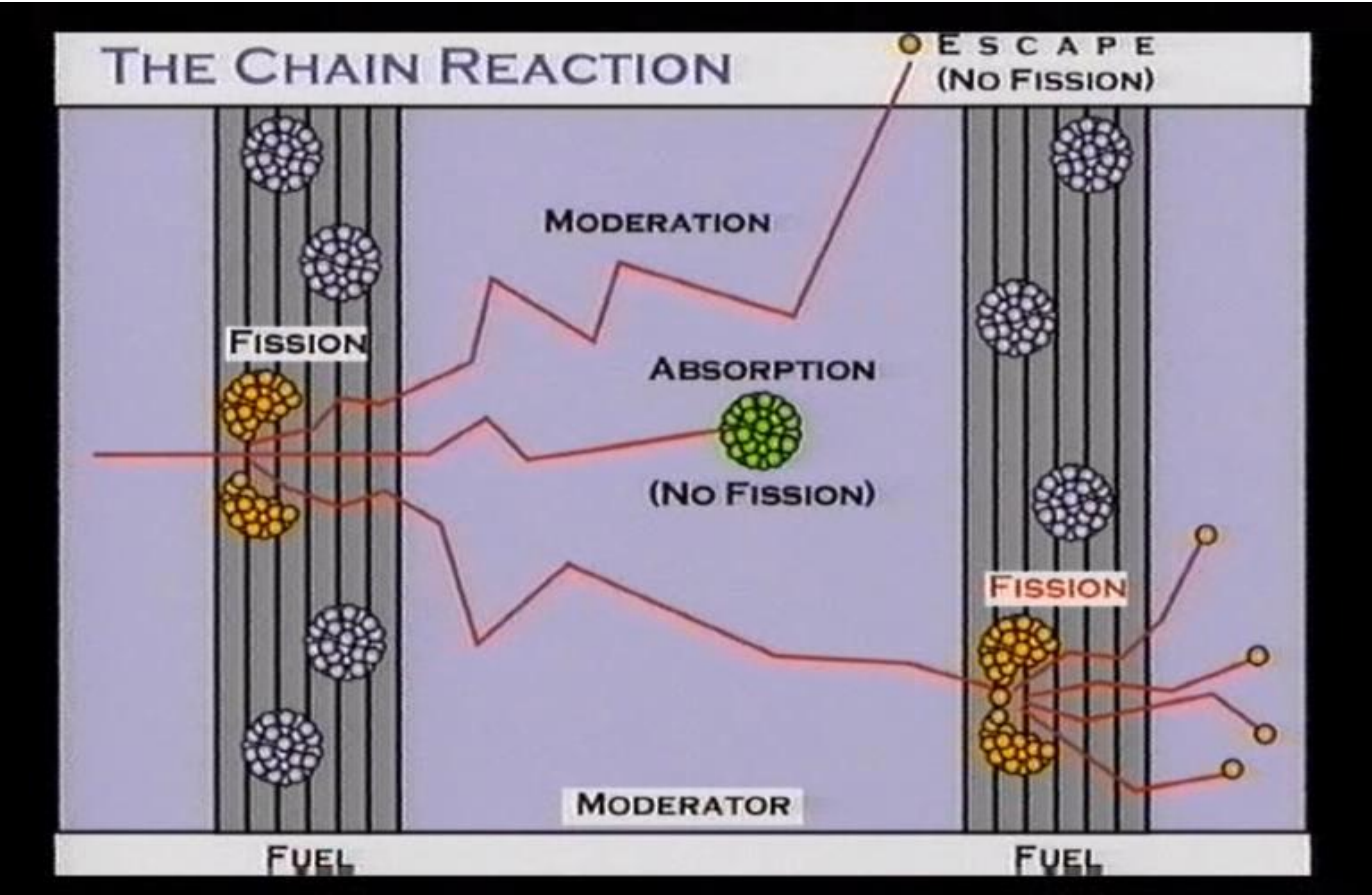


Fission: The Chain Reaction



Description of the chain reaction

Neutron multiplication factor: $$k_{eff} = \frac{N_{i+1}}{N_i}$$ (definition)

If
$$\begin{cases} k_{eff} < 1, & \text{the chain reaction slows down (subcritical)} \\ k_{eff} = 1, & \text{the chain reaction is constant (critical)} \\ k_{eff} > 1, & \text{the chain reaction is growing (supercritical)} \end{cases}$$

Reactivity: $$\rho = \frac{k_{eff} - 1}{k_{eff}}$$ (definition)

Uncontrolled liberation of energy: atomic bomb
Controlled: nuclear reactor

The nuclear power plant