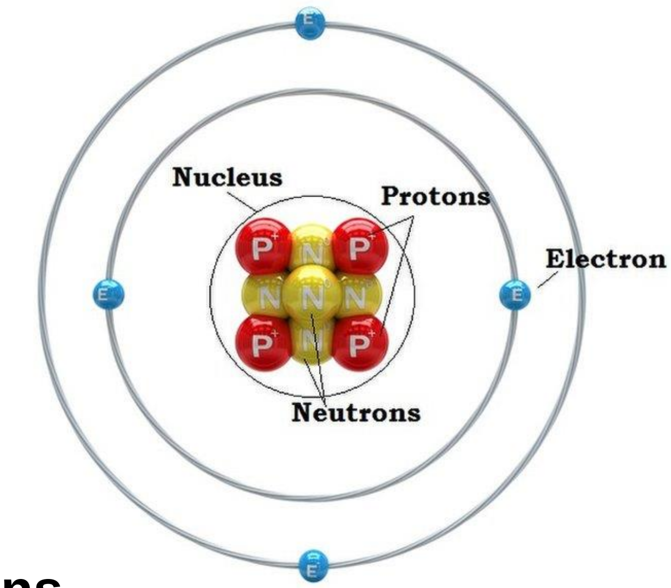
STRUCTURE OF ATOMS



electron cloud: electrons

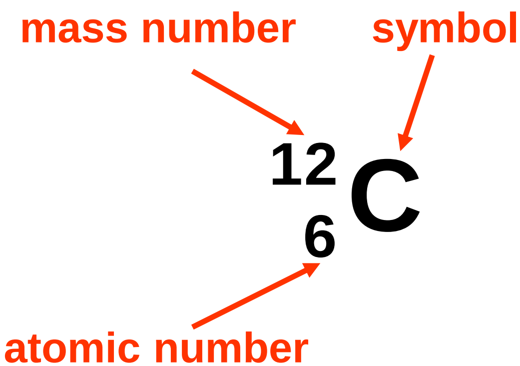
nucleus: protons, neutrons → nucleons

	mass (amu)	electric charge
Electron (e^-)	0.00055	–1e
Proton (p^+)	1.00728	+1e
Neutron (n^0)	1.00866	0

$$e = \frac{F}{N_A} = 1.602 \times 10^{-19} \mathrm{C}$$

ATOMIC NUMBER (Z) = Number of protons in an atom's nucleus

MASS NUMBER (A) = Number of protons (Z) + Number of neutrons (N)



carbon - 12

RELATIVE ATOMIC MASS

dimensionless physical quantity defined as the ratio of the mass of one atom of a given chemical element to the unified atomic mass unit.

<u>atomic mass unit (amu):</u>

earlier: **H as the smallest atom (1803, Dalton)**

1/16 of the mass of an O atom (Ostwald, 1903)

Since 1961: exactly 1/12 of the mass of a ^{12}C (1.660539×10^{-27} kg)

Isotopes

atoms with identical atomic numbers (Z) but different mass numbers (A) (= identical proton number, but different neutron number)

e.g.: hydrogen:	**1 proton + 0 neutron (protium)**	**→ ^{1}H**
	1 proton + 1 neutron (deuterium)	**→ ^{2}H**
	1 proton + 2 neutrons (tritium)	**→ ^{3}H**

- **essentially the same chemical characteristics, but certain physical properties are different**
- **now more than 3300 isotopes are known (253 stable, ~80 unstable, but occur in nature, ~3000 artificial)**

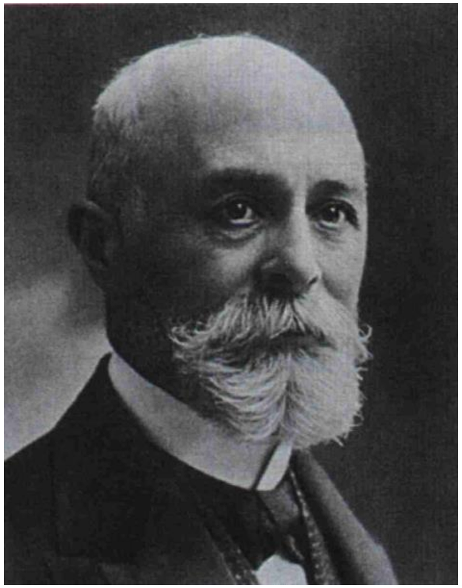
Many elements: mixtures of isotopes

Chlorine: 75.77% ^{35}Cl 34.969 amu and 24.23% ^{37}Cl 36.966 amu

Average relative atomic mass of chlorine:

0.7577×34.969 amu + 0.2423×36.966 amu = <u>35.46 amu</u>

Discovery of radioactivity



- study of luminescence
- used ores containing uranium: if they emit radiation after being exposed to sunlight
- used photographic plates
- March 1896: some plates that have not been exposed to light showed IMAGES

new radiation: not luminescence because the radiation does not require exposure to light

Antoine Henry Becquerel (1852-1908)

Pierre Curie (1859-1906), Marie Curie-Sklodowska (1867-1934)

introduced the term 'radioactivity'

studied radioactivity in detail

discovered new elements: Ra, Po

identified three different types of radiation

1903: Nobel prize in chemistry

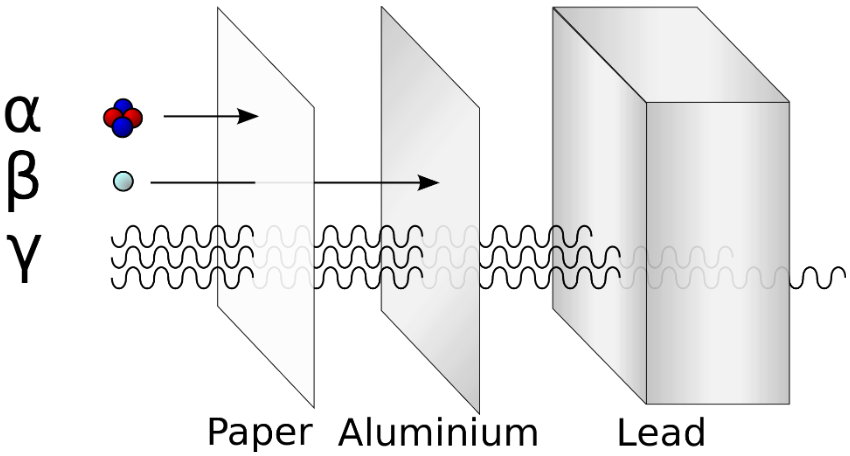
Radioactivity

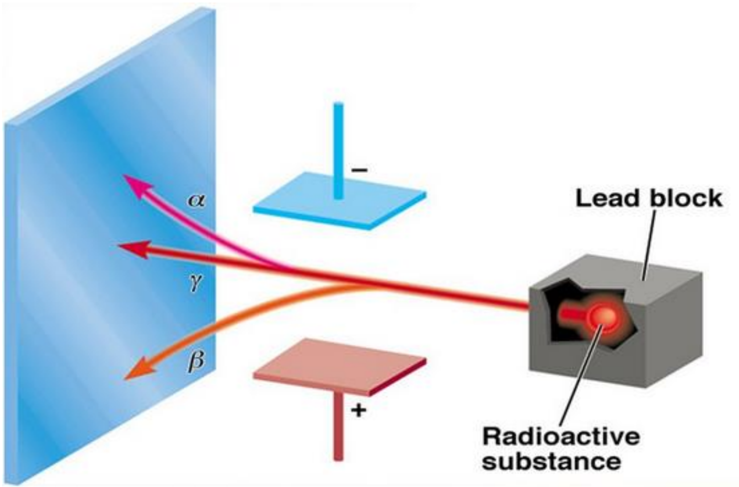
Radioactive decay: spontaneous nuclear reaction involving one nuclide only. It is always accompanied by radiation.

alpha (α) radiation: $^{4}He^{2+}$ ions (helium-4 nuclei)
positively charged heavy particles → interacts strongly with matter, small penetration

beta (β) radiation: electrons
negatively charged light particles, intermediate penetration

gamma (γ) radiation: electromagnetic radiation with extremely high energy, composed of photons which have neither mass nor electric charge (neutral) → penetrates the furthest





Radioactive decay types

α **decay: emission of an α particle form the nucleus,**
α and usually γ radiation

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

$$\text{General}: \quad ^{A}_{Z}E \rightarrow ^{A-4}_{Z-2}E' + ^{4}_{2}He$$

β^- **decay: emission of an electron from the nucleus by the conversion of one neutron to proton**
β and usually γ radiation

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe + e^-$$

$$\text{General}: \quad ^{A}_{Z}E \rightarrow ^{A}_{Z+1}E' + e^-$$

Simplified: $n^0 \rightarrow p^+ + e^-$

Radioactive decay types

β^+ decay: emission of a positron (e^+, electron-like particle with positive charge) from the nucleus by the conversion of one proton to neutron

usually only γ radiation

$$^{40}_{19}K \rightarrow {}^{40}_{18}Ar + e^+$$

$$\text{General}: \quad ^{A}_{Z}E \rightarrow {}^{A}_{Z-1}E' + e^+$$

Simplified: $p^+ \rightarrow n^0 + e^+$

electron capture: capture of an electron from the electron cloud in the nucleus

usually only γ radiation

$$^{197}_{80}Hg + e^- \rightarrow {}^{197}_{79}Au$$

$$\text{General}: \quad ^{A}_{Z}E + e^- \rightarrow {}^{A}_{Z-1}E'$$

Simplified: $p^+ + e^- \rightarrow n^0$

Radioactive decay types

isomeric decay: energy change within the nucleus without any noticeable change in composition

only γ radiation

$$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc$$

$$\text{General}: \quad ^{Am}_{Z}E \rightarrow ^{A}_{Z}E'$$

***m*: metastable nucleus, an excited nucleus with excess energy**

RADIOACTIVE DECAY SERIES

The product of a radioactive decay can also be radioactive

$$^{238}U \xrightarrow{\alpha} {}^{234}Th \xrightarrow{\beta^-} {}^{234}Pa \xrightarrow{\beta^-} {}^{234}U \xrightarrow{\alpha} {}^{230}Th \xrightarrow{\alpha} {}^{226}Ra$$

$$\xrightarrow{\alpha} {}^{222}Rn \xrightarrow{\alpha} {}^{218}Po \xrightarrow{\alpha} {}^{214}Pb \xrightarrow{\beta^-} {}^{214}Bi \xrightarrow{\beta^-} {}^{214}Po$$

$$\xrightarrow{\alpha} {}^{210}Pb \xrightarrow{\beta^-} {}^{210}Bi \xrightarrow{\beta^-} {}^{210}Po \xrightarrow{\alpha} {}^{206}Pb$$

Four decay series:

	$^{232}Th \rightarrow ... \rightarrow {}^{208}Pb$	(4n)
	$^{237}Np \rightarrow ... \rightarrow {}^{205}Tl$	(4n+1)*
	$^{238}U \rightarrow ... \rightarrow {}^{206}Pb$	(4n+2)
	$^{235}U \rightarrow ... \rightarrow {}^{207}Pb$	(4n+3)

* does not occur in nature, because the half-life of the parent isotope is too short ($t_{½}$ = 2.1×10^6 year)

NUCLEAR STABILITY

Stable isotopes: no radioactive decay is detectable

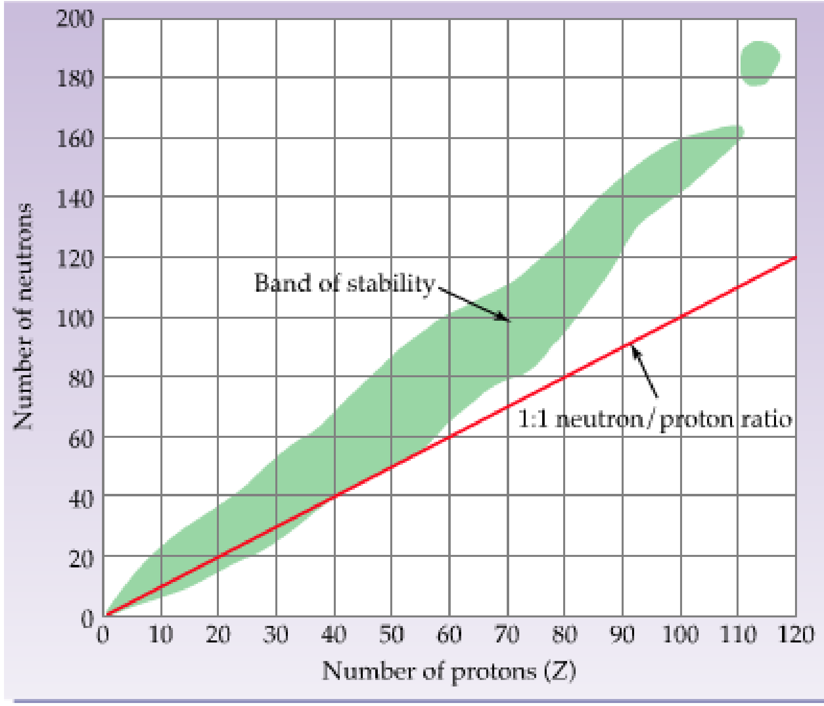
- **low atomic numbers ⇒ number of neutrons is close to number of protons (n/p ~ 1) e.g.** $^{12}_{6}C$, $^{14}_{7}N$, $^{16}_{8}O$, $^{19}_{9}F$, $^{23}_{11}Na$, $^{40}_{20}Ca$

- **high atomic numbers ⇒ gradually increasing excess of neutrons (n/p ~ 1.5) e.g.** $^{55}_{25}Mn$, $^{75}_{33}As$, $^{132}_{54}Xe$, $^{169}_{69}Tm$, $^{208}_{82}Pb$

- **even numbers for both protons and neutrons are favored**
- **some elements with high even atomic number have a lot of stable isotopes**

$_{50}Sn$ → 10 stable isotopes

$_{54}Xe$ → 9 stable isotopes



RADIOACTIVE ISOTOPES

Every element has at least one radioactive isotope (which does not necessarily occur in nature)

$_{43}$Tc and $_{61}$Pm do not have stable isotopes

Elements after $_{82}$Pb do not have stable nuclides, although some radioactive isotopes have very long half-lives

^{209}Bi $t_{½}$ = 1.9 × 10^{19} years hardly detectable!

^{238}U $t_{½}$ = 4.5 × 10^{9} years

Why do radioactive isotopes occur in nature?

A) very long half-life ^{40}K 1.3 × 10^{9} years

^{238}U 4.5 × 10^{9} years

estimated age of the Earth 5 × 10^{9} years

estimated age of the Universe 1.3 × 10^{10} years

SHORT-LIVED RADIOACTIVE ISOTOPES

B) continuously produced by the radioactive decay series

Ra occurs in nature. Although the longest-lived isotope ^{226}Ra has $t_{1/2}$ = 1.6 × 10^3 years

produced in the decay series starting from ^{238}U

C) produced by nonspontaneous nuclear reactions driven by energetic cosmic rays

^{3}H $t_{1/2}$ = 12.3 years

$$^{14}_{7}N + n \rightarrow {}^{12}_{6}C + {}^{3}_{1}H$$

^{14}C $t_{1/2}$ = 5730 years

$$^{14}_{7}N + n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

A small steady-state concentration is kept up by the equilibrium of continuous production and decay. ➡ **uses in radioactive dating**

Willard F. Libby (1908-1980)

1960: Nobel prize in chemistry

Radioactive dating

Radiocarbon dating, 1940s: tiny, but more or less stable concentration of ^{14}C in air due to the continuous production and decay

Production (cosmic rays): $^{14}N + n \rightarrow {}^{14}C + {}^{1}H$

Decay (β^-): $^{14}C \rightarrow {}^{14}N + e^-$ **$t_{1/2}$ = 5730 ± 40 years**

^{14}C combines with the oxygen in the atmosphere to form carbon dioxide ($^{14}CO_2$),

- **dissolves in the ocean**
- **taken up by plants via photosynthesis**
- **animals eat the plants,**

→ ^{14}C is distributed throughout the biosphere

Organism (plant or animal) dies → carbon input ceases → $^{14}C/^{12}C$ decreases

Upper limit ~50 000 years

BINDING ENERGY IN THE NUCLEUS

^{4}He: 2 protons + 2 neutrons + 2 electrons

Mass of 2 protons: $2 \times 1.00728 = 2.01456$ amu

Mass of 2 neutrons: $2 \times 1.00866 = 2.01732$ amu

Mass of 2 electrons: $2 \times 0.00055 = 0.00110$ amu

4.03298 amu

Mass of ^{4}He atom: 4.00260 amu

MASS DEFECT: The mass of an atom is less than the sum of the individual masses of the free constituents

true for every atom or nucleus!

For ^{4}He

$$\Delta m = \Sigma m_{proton,neutron,electron} - m_{atom} = 0.03038 \text{ amu}$$

BINDING ENERGY IN THE NUCLEUS

Einstein equation: $\Delta E = \Delta m c^2$

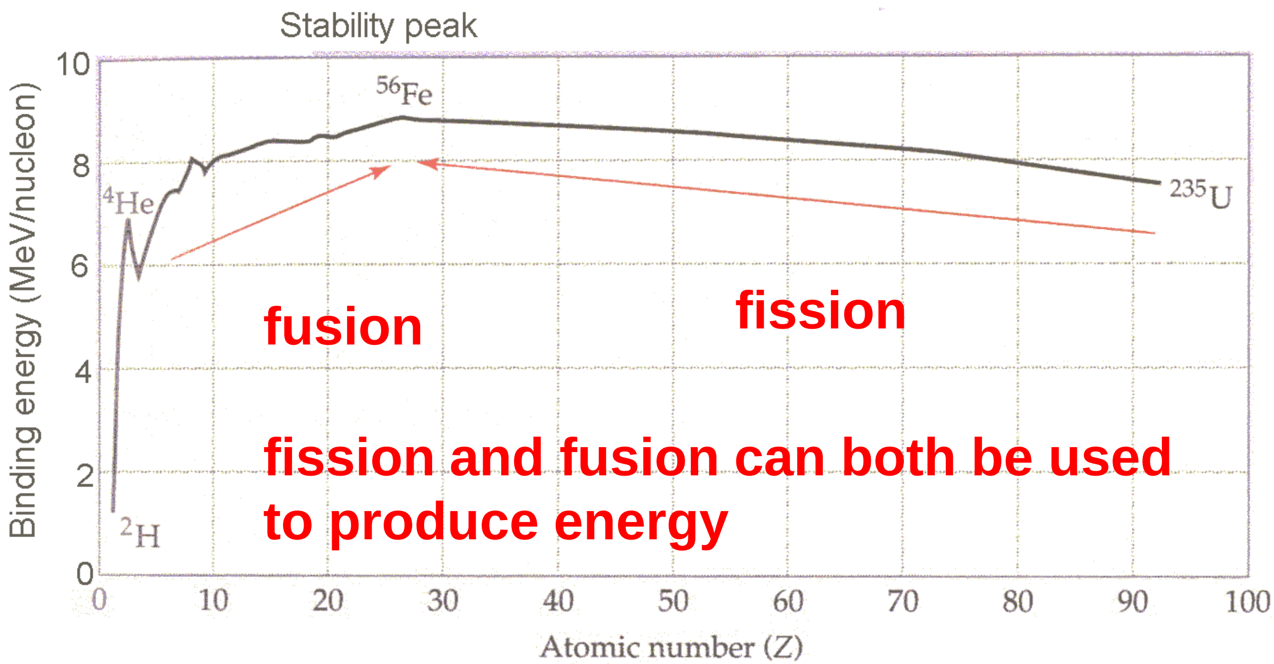
***c*, speed of light, 3.00 × 10⁸ ms⁻¹**

$\Delta E = 2.73 \times 10^{12}\ \mathrm{Jmol^{-1}} = 2.73 \times 10^{9}\ \mathrm{kJmol^{-1}}$

Binding energy of a nucleus: **energy that would be required to disassemble the nucleus of an atom into its component parts**

$$\Delta E_{nucleon} = \frac{\Delta E}{A}$$

average binding energy per nucleon



NUCLEAR REACTIONS

nuclides

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

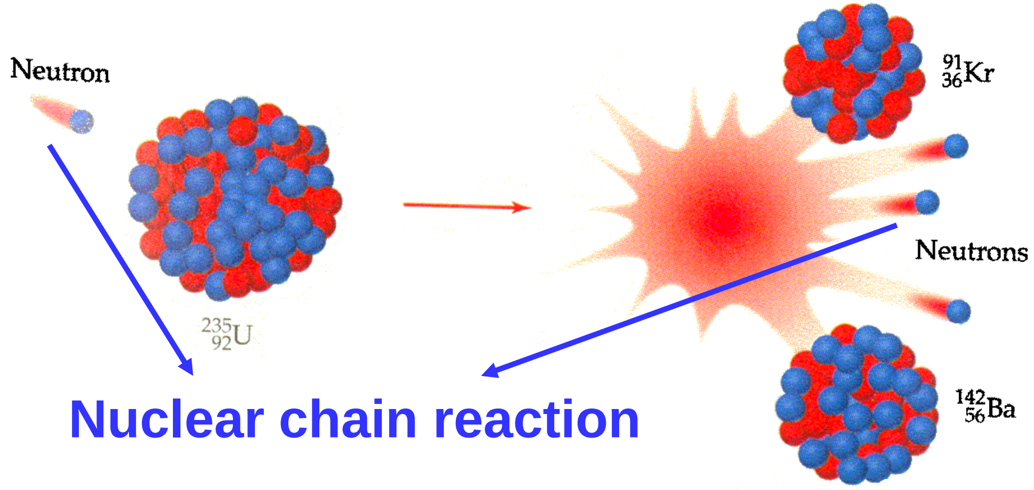
nuclear equation

- **A nuclear reaction involves a change in an atom's nucleus, usually producing a different element.**
- **Involves the collision of two nuclei or a nucleus and a subatomic particle → induced changing in a nuclide (radioactive decays are NOT nuclear reactions)**
- **Different isotopes of an element: essentially the same in chemical reactions BUT often quite different in nuclear reactions.**
- **The rate of a nuclear reaction is unaffected by T, p, or a catalyst.**
- **The nuclear reaction of an isotope is essentially the same, regardless of its actual chemical form.**
- **Energy change of nuclear reactions >> energy change of chemical reactions.**

Nuclear fission

- **the nucleus of an atom splits into smaller parts**
- **it commonly occurs on the impact of a smaller particle (e.g. neutron), but spontaneous fragmentation of a nucleus is also known (if Z is large e.g. ^{250}Cm, ^{252}Cf)**

$$^{235}_{92}U + n \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3n$$



December 1938: discovery of nuclear fission of heavy elements (Otto Hahn, Fritz Strassmann)

O. Hahn: Nobel Prize in Chemistry, 1944

January 1939: theoretical explanation (Lise Meitner, Otto Robert Frisch)

Uses of nuclear fission:

- uncontrolled nuclear chain reaction: huge explosion, first-generation nuclear weapons
- controlled nuclear chain reaction: nuclear reactors

Challenges of nuclear fission

- ^{235}U is only 0.7 % of natural uranium, needs to be enriched
- ^{239}Pu, ^{241}Pu can also be used for fission
    - they do not occur in nature → produced in nuclear reactors
- a lot of long-lived radioactive isotopes are produced by fission (nuclear waste)

Natural nuclear fission reactor

- Oklo, Gabon: ~2 billion years ago self-sustaining nuclear chain reactions occurred
- key factors that made it possible: higher (~ 3.1%) ^{235}U-content and groundwater acted as a neutron moderator
- 3-hour-long cycles continued for hundreds of thousands years

Nuclear power plants

thermal power station in which the heat source is a nuclear reactor

1942, Chicago, USA: first artificial nuclear reactor (L. Szilárd, E. Fermi)

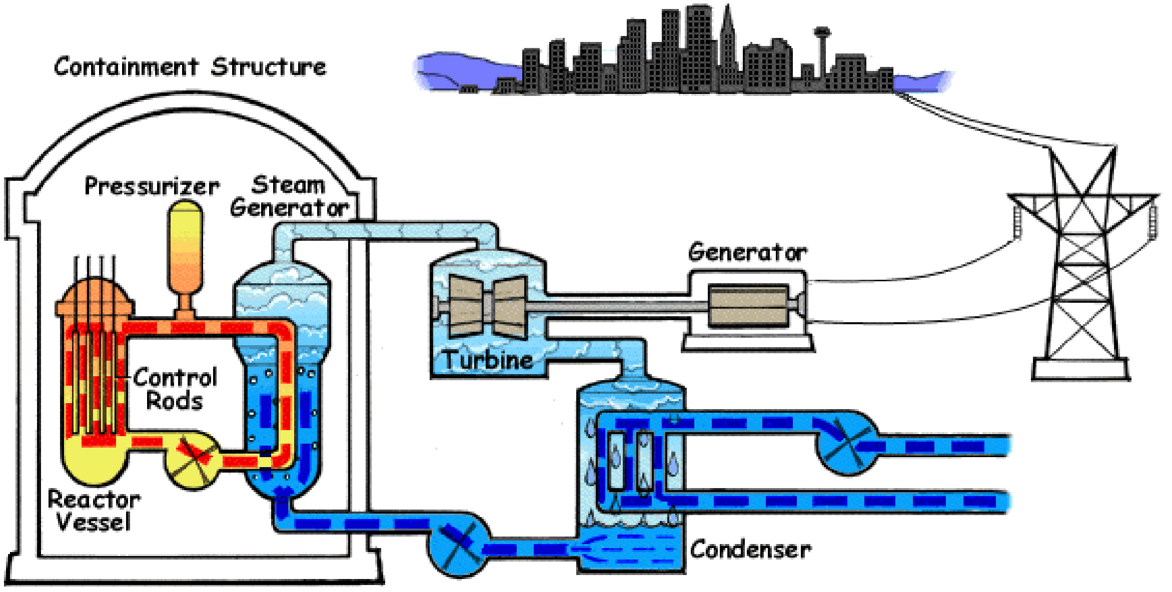
1948, Oak Ridge, USA: first nuclear reactor generating enough electricity to power a light bulb

1951, Arco, USA: first nuclear power plant for experimental purposes

1954, Obninsk, Soviet Union: first nuclear power plant for civil purposes

1956, Calder Hall, England: first commercial nuclear power station

As of today ~450 nuclear power plants operate worldwide



Pressurized water reactor (PWR)

Atomic bomb

August 1939: Albert Einstein's letter to president Roosevelt → Manhattan project

16 July 1945: first atomic bomb, New Mexico

6 and 9 August 1945: bombings of Hiroshima and Nagasaki, Japan

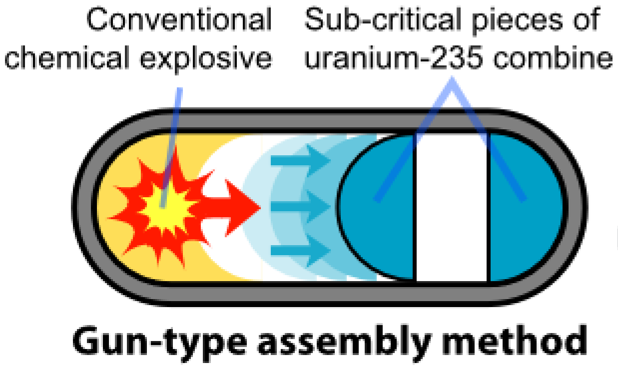
August 1949: Soviet Union tested its first fission bomb

Since the 1950s nuclear weapons have been detonated over two thousand times for testing and demonstration

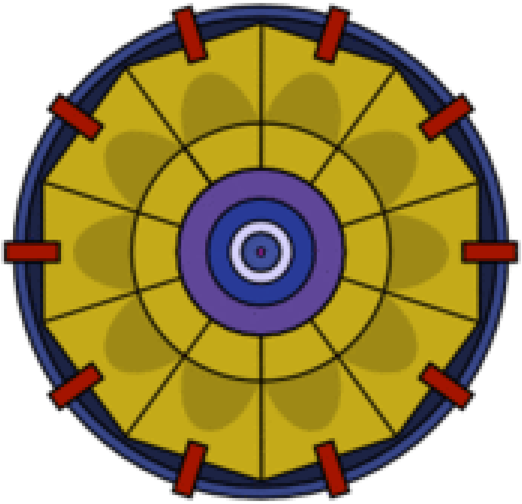
Fission bomb:

^{235}U: enrichment of natural uranium (gun method)

^{239}Pu: synthesis in nuclear reactors from ^{238}U by nuclear reactions (implosion method)



Little boy



Trinity, Fat man, RDS-1

Nuclear fusion

build-up of nuclei from lighter nuclei

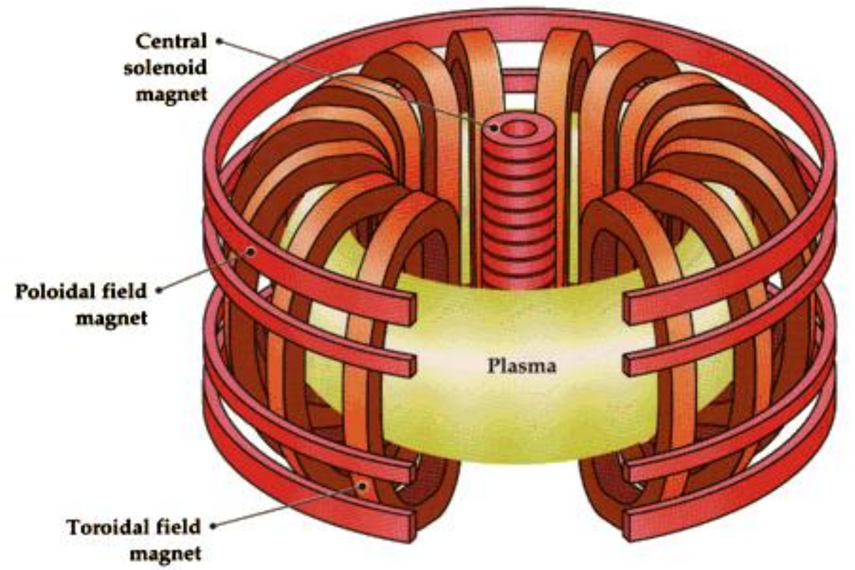
$^{1}H + ^{1}H \rightarrow ^{2}H + e^{-}$

$^{1}H + ^{2}H \rightarrow ^{3}He$

$^{3}He + ^{3}He \rightarrow ^{4}He + 2\ ^{1}H$

$^{3}He + ^{1}H \rightarrow ^{4}He + e^{-}$

overall: $4\ ^{1}H \rightarrow ^{4}He + 2\ e^{-}$



Importance:

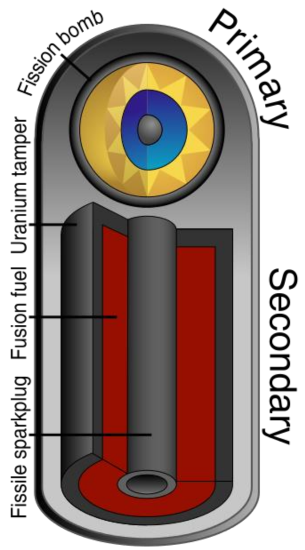
- energy producing processes in stars
- not suitable for energy production at present (TOKAMAK, no nuclear waste produced)
- much more efficient nuclear weapons (hydrogen bomb)

thermonuclear weapon/second generation nuclear weapon

1951 USA: Edward Teller and Stanislaw Ulam

1955 Soviet Union: Andrei Sakharov

Hydrogen bomb



1. implosion method fission bomb

2. fusion reaction

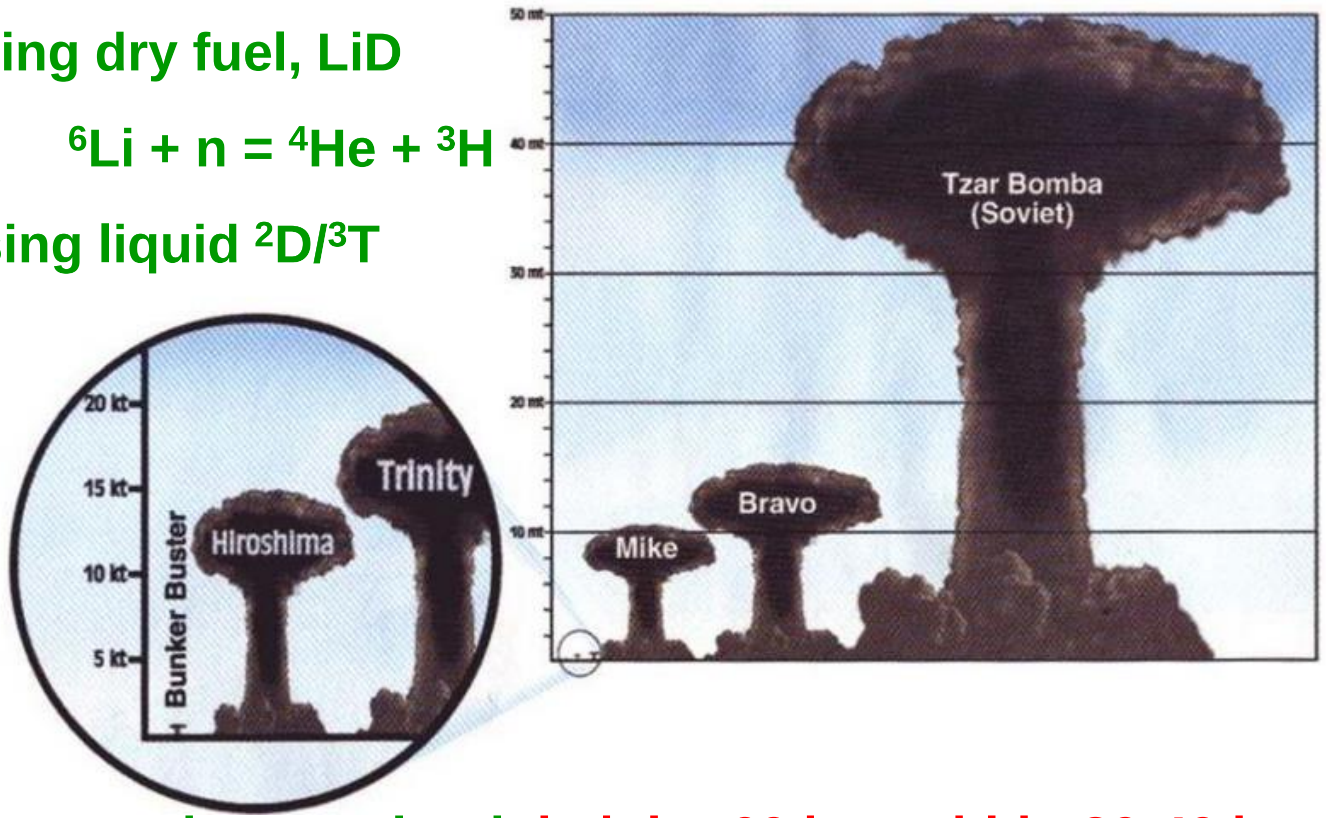
a) using dry fuel, LiD

$^{6}Li + n = {}^{4}He + {}^{3}H$

b) using liquid $^{2}D/^{3}T$

Tsar bomb: 3 stages

1. implosion method fission bomb
2. fusion of $^{2}D/^{3}T$
3. fission of ^{238}U



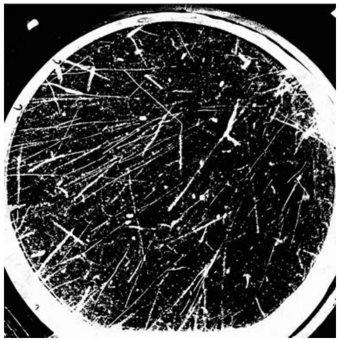
mushroom cloud: height: 60 km, width: 30-40 km

30th Oct 1961, Novaya Zemlya

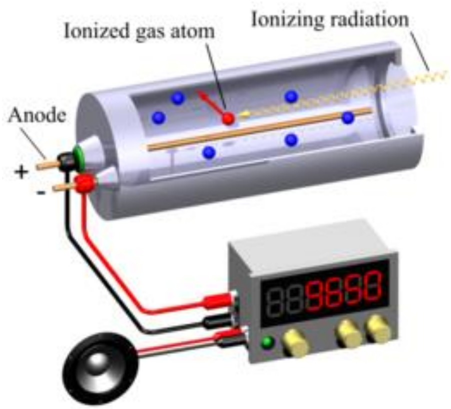
~97% of the energy resulted from thermonuclear fusion → one of the "cleanest" nuclear bombs ever created, hardly any radioactive waste

DETECTION OF RADIOACTIVITY

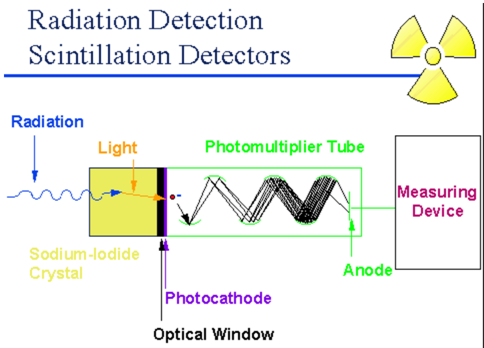
ionizing effect = 'ionizing radiation' (α, β, γ): radiation that carries enough energy to liberate electrons from atoms or molecules



- **cloud chamber, bubble chamber**: based on phase changes
  ionization → supersaturated vapor condensates forming a mist-like trail or bubbles form in a superheated liquid



- **Geiger-Müller counter**: filled with an inert gas. ionization → electrons and ions form that flow towards the electrodes → electricity



- **scintillation counters**: ionization → light pulses

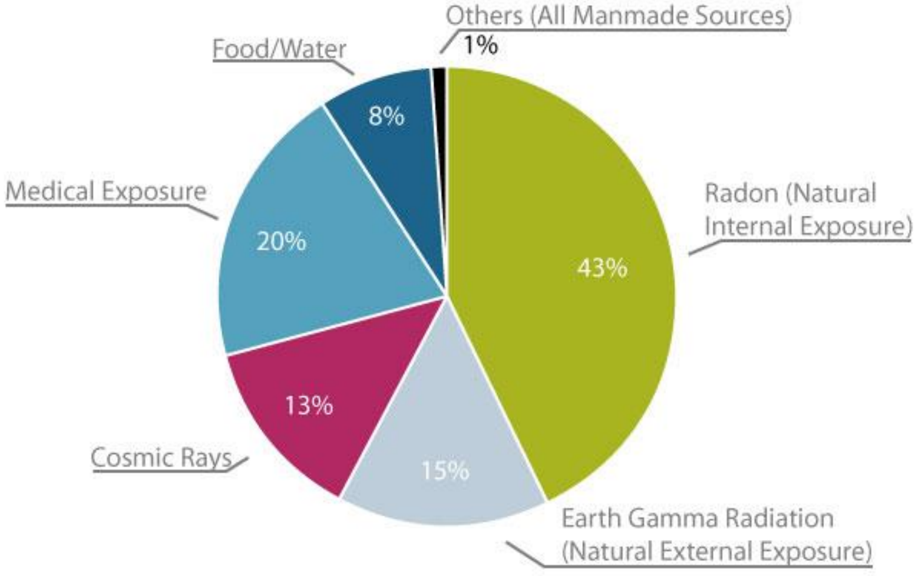
LIVING WITH RADIOACTIVITY

Radioactivity is *natural*: it is always around as background radiation at low levels, it may come from space, soil, plants, food, everyday objects, our own bodies…

Through billions of years, living organisms adapted to the background radiation → no detectable effect

Artificial radiation:

- **Smaller part: nuclear weapons, nuclear accidents, nuclear power plants**
- **Larger part: medical imaging, radiation therapy**

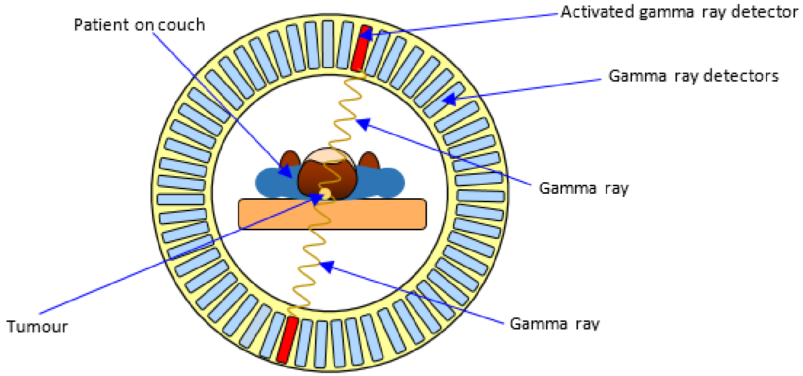


Applications of radioactive isotopes

general: radioactive tracing, George Hevesy, Nobel prize in chemistry, 1943

Isotope	Application	Decay	Half-life
^{3}H	dating (water, wine)	β^-	12.3 years
^{14}C	radiocarbon dating	β^-	5730 years
^{18}F	PET scans	β^+	110 min
^{32}P	leukemia therapy, labelling of DNA	β^-	14.3 days
^{40}K	dating (rocks)	β^+	1.3×10^9 years

radioluminescence triggered by the decay of tritium



Positron emission tomography (PET) scanner

Applications of radioactive isotopes

Isotope	Application	Decay	Half-life
^{60}Co	cancer therapy, sterilization	β^-, γ	5.3 years
^{99m}Tc	brain, heart, bone scans	γ	6.0 h
^{123}I	thyroid scans (SPECT)	e. c., γ	13.3 h
^{235}U	atomic bomb, nuclear plant	α	7.0×10^8 years

Security screening of cars at the Super Bowl using ^{60}Co gamma scanner