School of Industrial and Information Engineering
Course 096125 (095857)
Introduction to Green and Sustainable Chemistry

POLITECNICO DI MILANO

Nuclear Energy.

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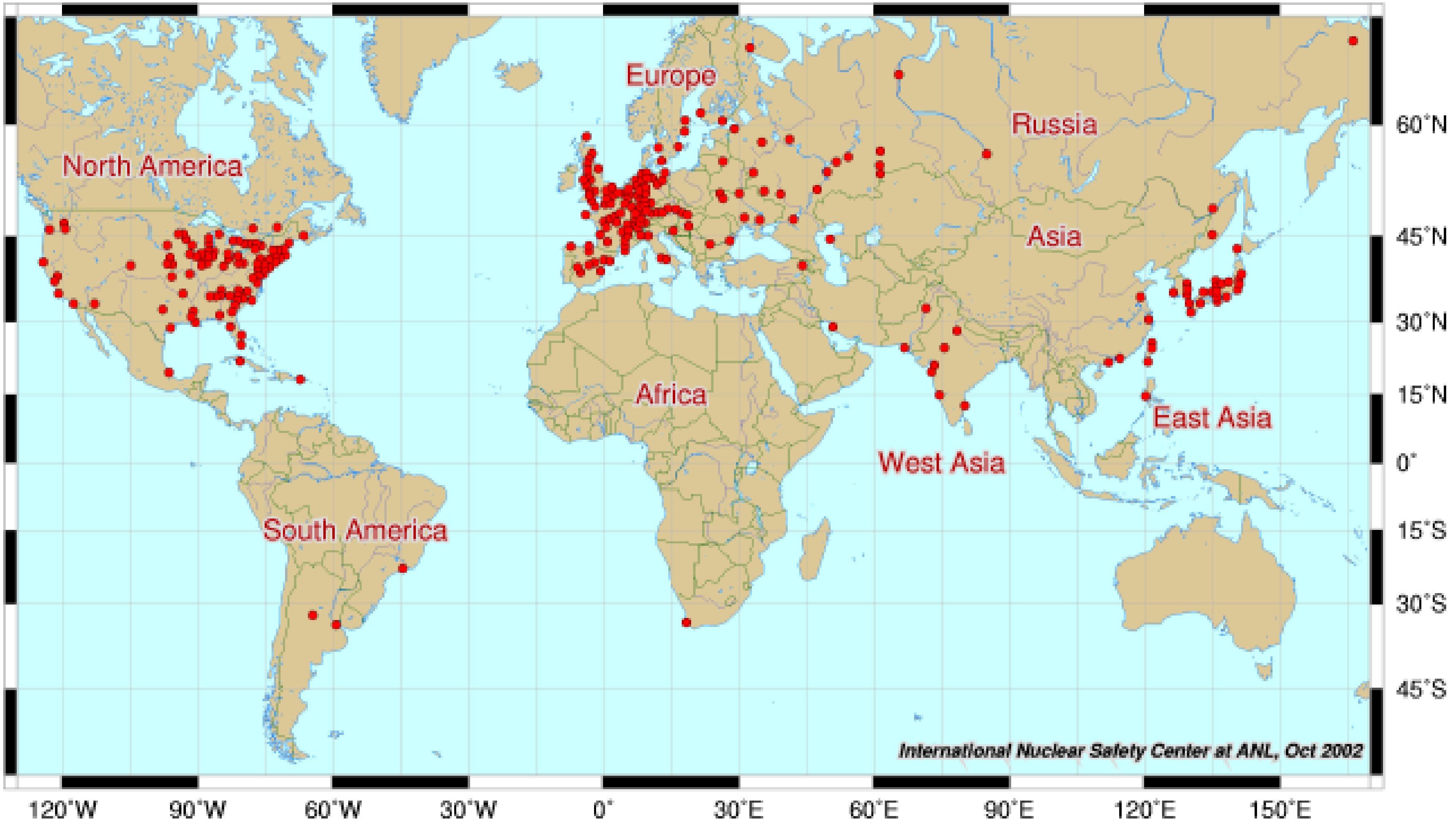
https://iscamapweb.chem.polimi.it/citterio/it/education/course-topics/

World Nuclear Power Plants.



International Nuclear Safety Center at ANL, Oct 2002

Nuclear Energy: Fusion and Fission.

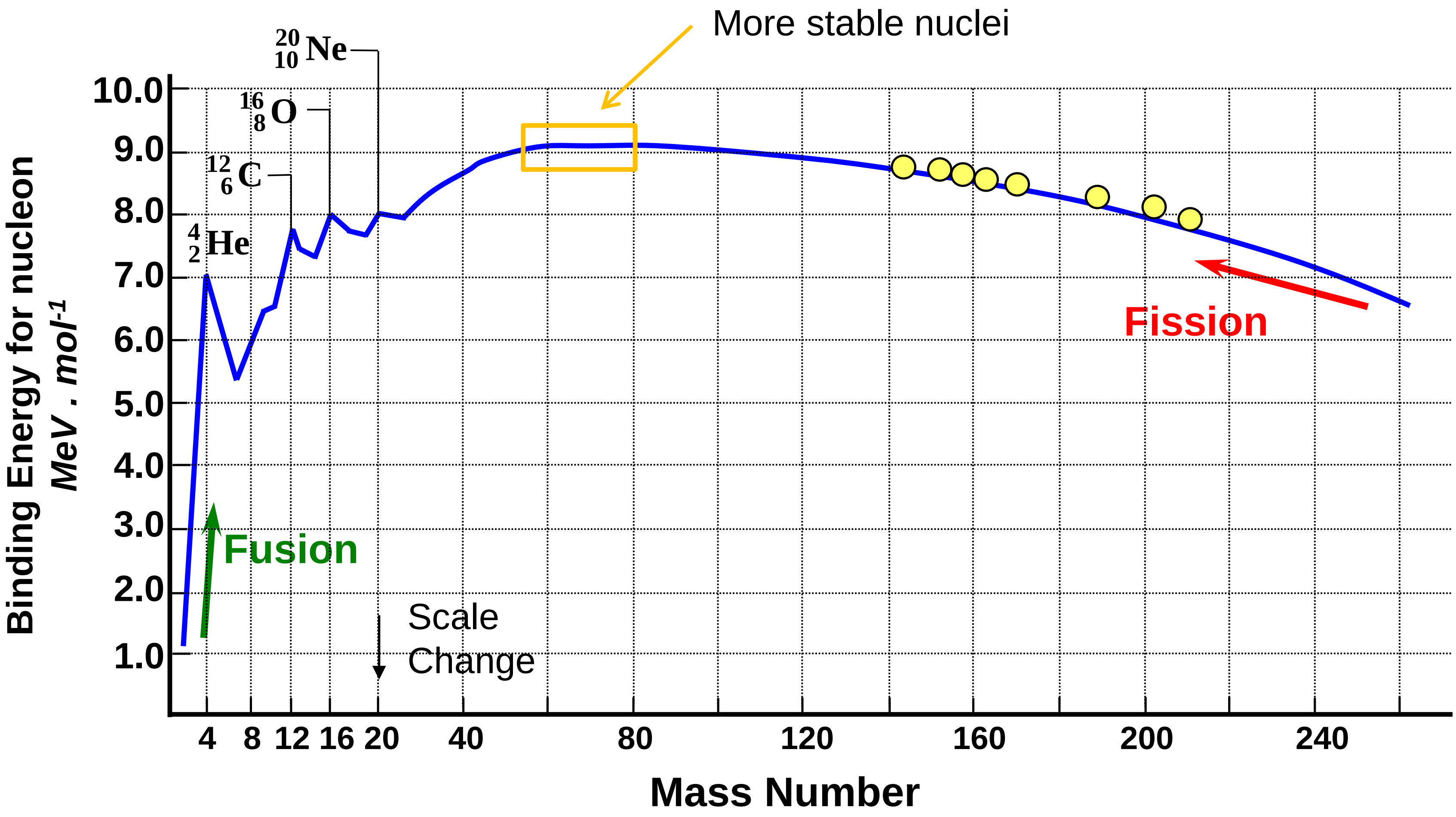
Fusion

- As nuclei of two light atoms are brought closer to each other, the electrostatic repulsion (due to positively-charged protons) increases. If the activation energy to overcome the repulsive forces is provided, two unstable nuclei *fuse* together into a larger stable nuclei, releasing the excess binding energy in the process.
- Examples are reaction in the Sun and in thermonuclear (hydrogen) bombs.

Fission

- In nature, some nuclei are unstable towards decomposition into small nuclei fragments (natural radioactivity), other nuclei were found unstable after preparation by humans (artificial radioactivity).
- Examples are radioactive decomposition of Radium and Uranium (*natural*) and Plutonium (*artificial*) and in nuclear (U-235) bombs.

Nuclei Stability.



Nuclear Reactions: Fusion vs. Fission.

- Fusion:

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n \quad + 17.6\ \mathrm{MeV/nucleus} $$

(ΔE = 3.3×10^{14} J·kg^{-1} deuterium)

- Fission

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\ {}^{1}_{0}n + 202\ \mathrm{MeV/nucleus} = 3.24\times10^{-11}\mathrm{J/nucleus} $$

(ΔE = 8.3×10^{13} J·kg^{-1} U-235)

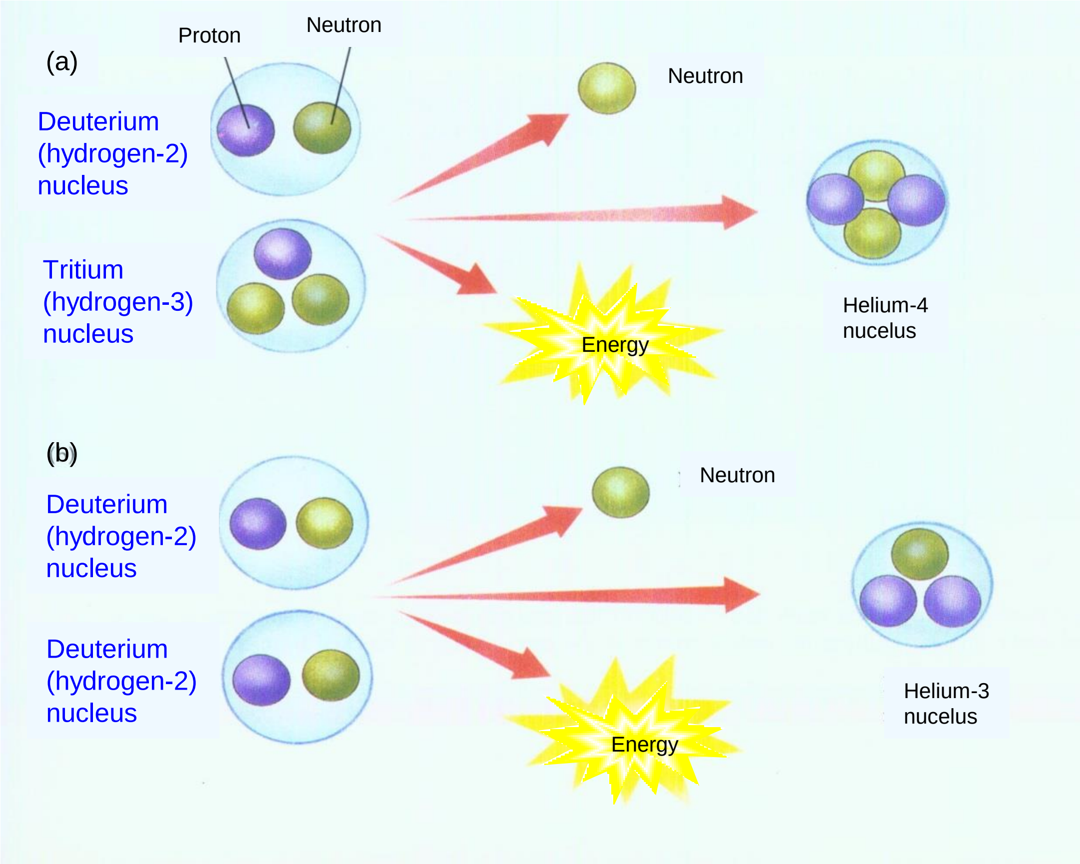
- *Coal (recall)*

$$ \mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2} \quad + 15000\ \mathrm{BTU/lb\ of\ coal} $$

(ΔE = 3.5×10^{7} J·kg^{-1} coal)

Fusion Reactions

- $^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}n \quad + 3.3\ \mathrm{MeV}\ (79\ \mathrm{GJ/g})\ \text{at}\ 400 \times 10^{6}\ °\mathrm{C}$
- $^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}n \quad + 17.6\ \mathrm{MeV}\ (331\ \mathrm{GJ/g})\ \text{at}\ 45 \times {`}10^{6}\ °\mathrm{C}$

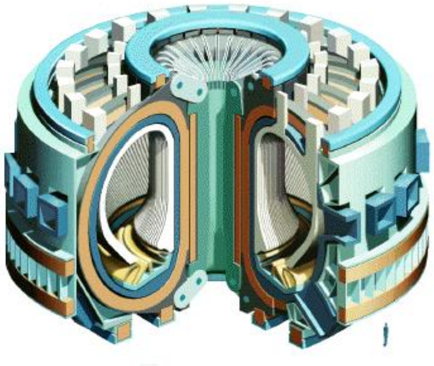


Breakeven Point and Challenges

- Where plasma can be raised at sufficiently high temperature and particle density, and long enough so the rate of energy production exceeds the rate of energy required for sustained reaction.

Challenges

- Ignition
  - Very high temperatures to overcome repulsive forces of positively charged nuclei
- Confinement
  - Very high pressures to increase probability of collision
  - And for times long enough for producing energy more than that required for heating and compression (sustained reaction)
    - No solid vessel
    - Magnetic confinement
    - Inertial confinement (laser)



Cold Confusion.[1]

- March 1989 two Utah professors (Pon & Fleishman) announced that they have achieved fusion in a jar (cold fusion).
- No body could ever verify their results.

[1] *For an account of the story, see "The Utah Fusion Circus", the New York Times. Editorial, April 30, 1989.*

Nuclear Weapons.

Controlled Reaction

Uncontrolled (Chain) Reaction

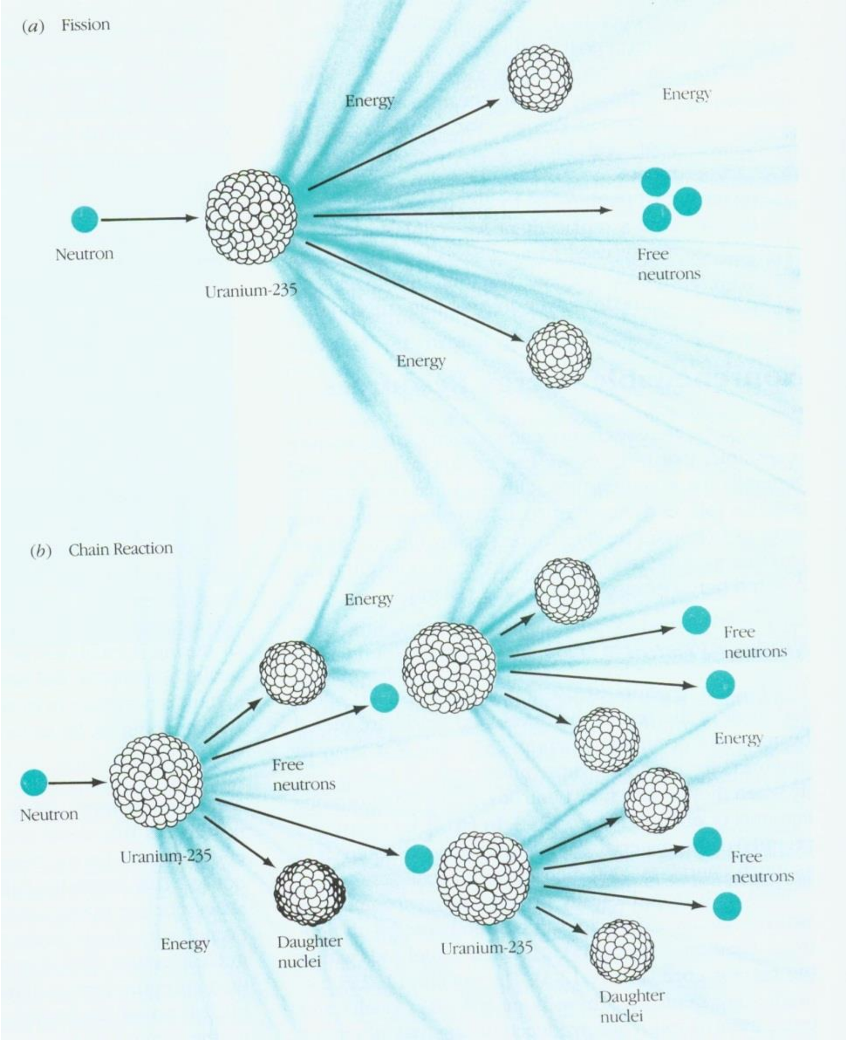
- Critical Mass (size of a baseball)

US Bombs

- Manhattan Project, Chicago, 1942
- Little Boy, Hiroshima (13 kilotons TNT), 1945
- Fat man, Nagasaki (22 kilotons TNT), 1945

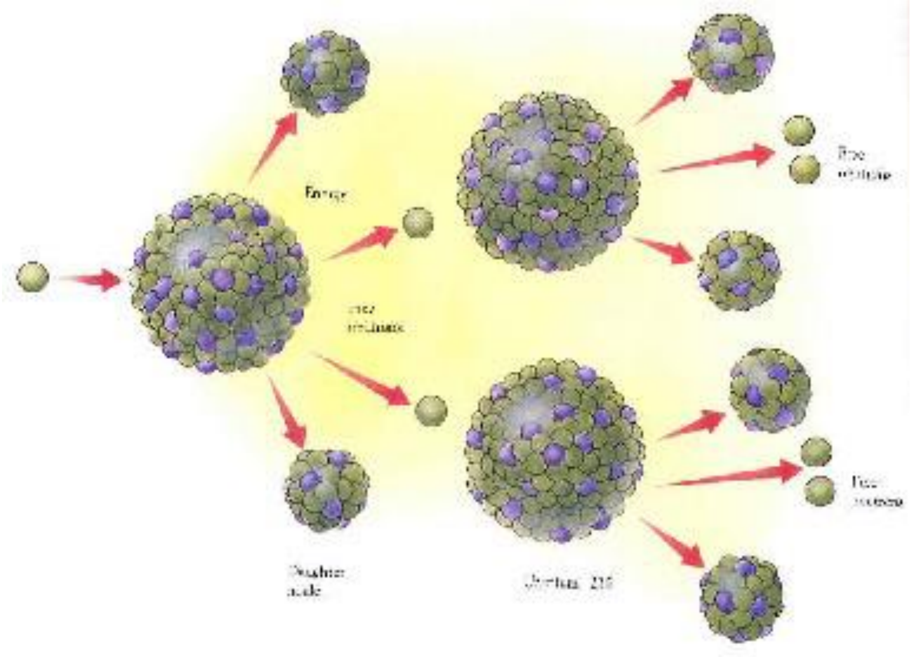
TNT

- tri-nitro-toluene=4.3×10^9 joules
- The bomb that used in the World Trade Center in New York was about 1 ton TNT



Atom Bomb and Nuclear Chain Processes.

Occurs when the produced neutrons are higher in number than those decomposed or unintercepted.



A nuclear chain reaction takes place. The critical mass of fissile material to auto-sustain the process is 5-15 Kg for Plutonium. Other fissile materials used as fuel in nuclear plants are U-235 and U-233.

Hydrogen Bombs.

- Isotopes of hydrogen and deuterium are fused to produce helium
- No limits to the explosive power
  - One has been tested with the explosive power of 68,000,000 tons of TNT
- Consequences are horrifically unclear
  - Nuclear Winter, Worldwide famine

Consequences of Nuclear Wars…

- Shock Effects
- Thermal Effects
- Radiation Effects

1-Megaton (Blast Distance from Ground zero)

- **1 mile**
  - Over-pressure: 43 psi
  - Winds: 1700 mph
  - Many Humans Killed
- **2 miles**
  - Over-pressure: 17 psi
  - Winds: 400 mph
  - Humans battered to death; lung hemorrhage; eardrums ruptured; Heavy machinery damaged
- **5 miles**
  - Over-pressure: 4psi
  - Winds: 130 mph
  - Bones fractured; All trees down; Buildings flattened
- **20 miles**
  - Over-pressure: Below 1 psi
  - Winds: Below 35 mph
  - Many broken windows

Natural and Artificial Radioactivity.

- Principles
- Decay types
- Nuclear Stability
- Decay kinetics
- Radioactive series

Atomic Decay.

Some atoms are less stable than others (see nucleogenesis) and, owing to the elapsed time, those having an half life < 10^8 years have just formed stable nuclei).

A radioactive isotope decay forming other nuclei until reach a more stable one.

Decay (natural decay) emitting:

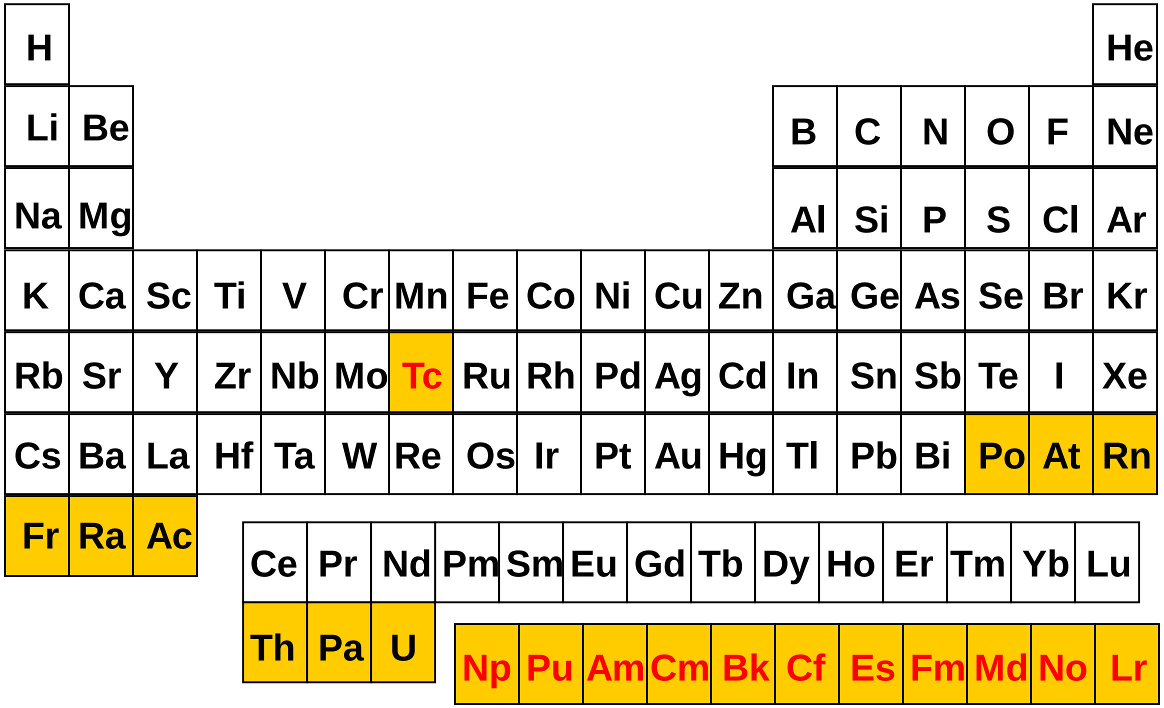
- mass (alpha particles)
- charge (beta particles)
- energy (gamma rays)

There are other types of decay but they are not observed in nature on earth.

Radioactivity.

The process where unstable nuclei decompose spontaneously with emission of high energy particles (rays).

Observed firstly by Becquerel in 1896.



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

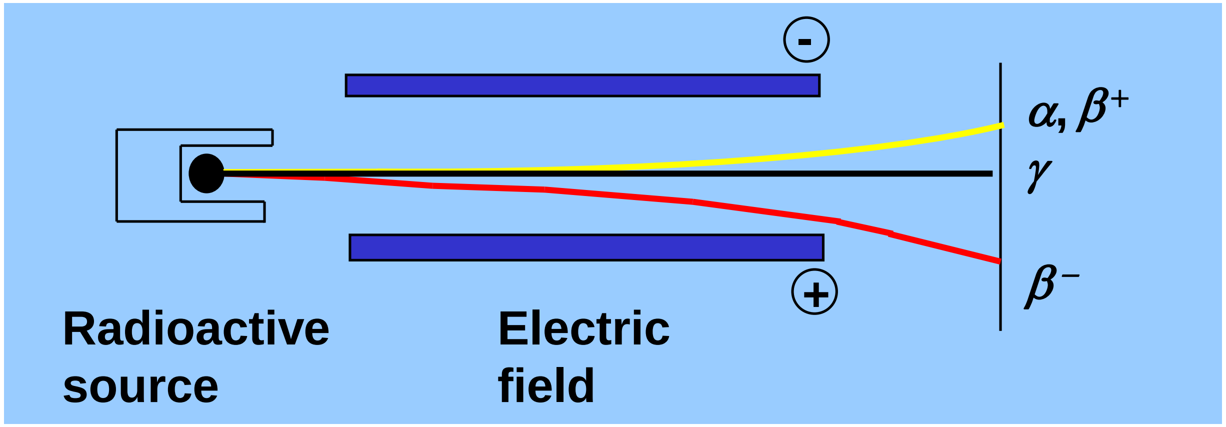
Radioactive elements

← **Artificial elements**

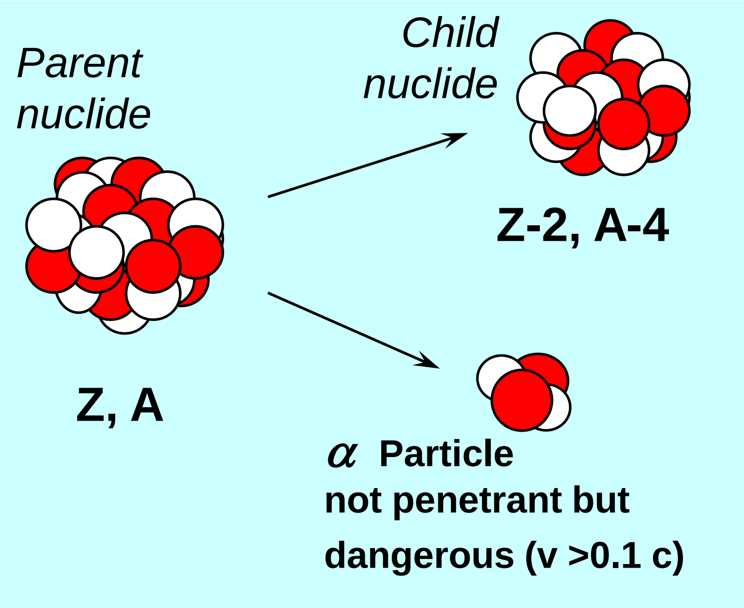
Radioactivity.

Main types of radioactivity:

- Alfa emissions $\alpha\left({}^{4}_{2}\mathrm{He}\right)$
- Beta emissions $\beta^{-}\left({}^{0}\mathrm{e}^{-1}\right)$
- Gamma emissions $\gamma\left({}^{0}_{0}\gamma\right)$
- Positron emissions $\beta^{+}\left({}^{0}\mathrm{e}^{+1}\right)$
- electronic capture (absorption of internal e^{-} by nucleus)



Three main Radioactive Decays.



Parent nuclide

Child nuclide

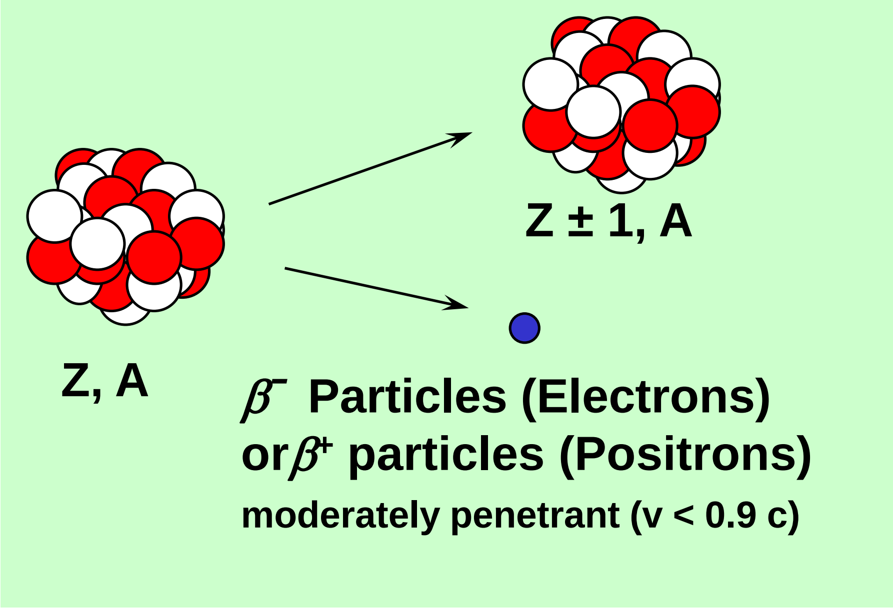
Z-2, A-4

Z, A

α Particle

not penetrant but

dangerous (v >0.1 c)



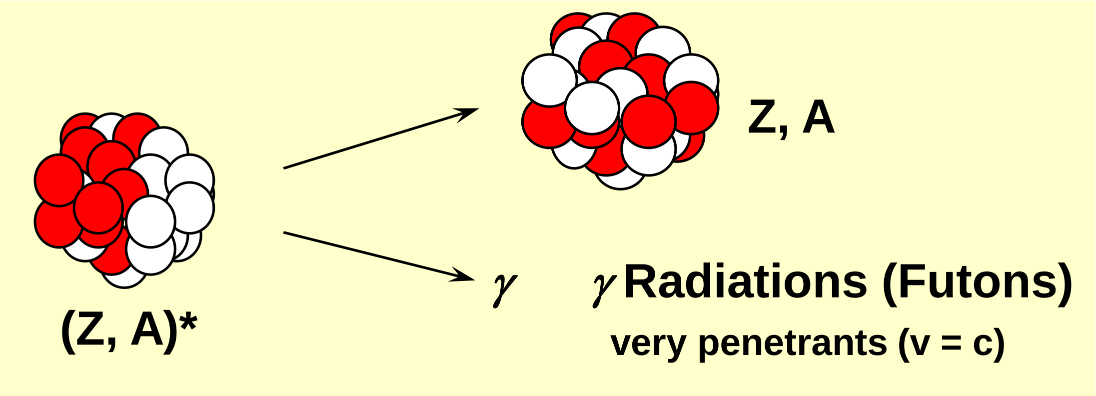
Z ± 1, A

Z, A

β^- Particles (Electrons)

or β^+ particles (Positrons)

moderately penetrant (v < 0.9 c)



Z, A

(Z, A)*

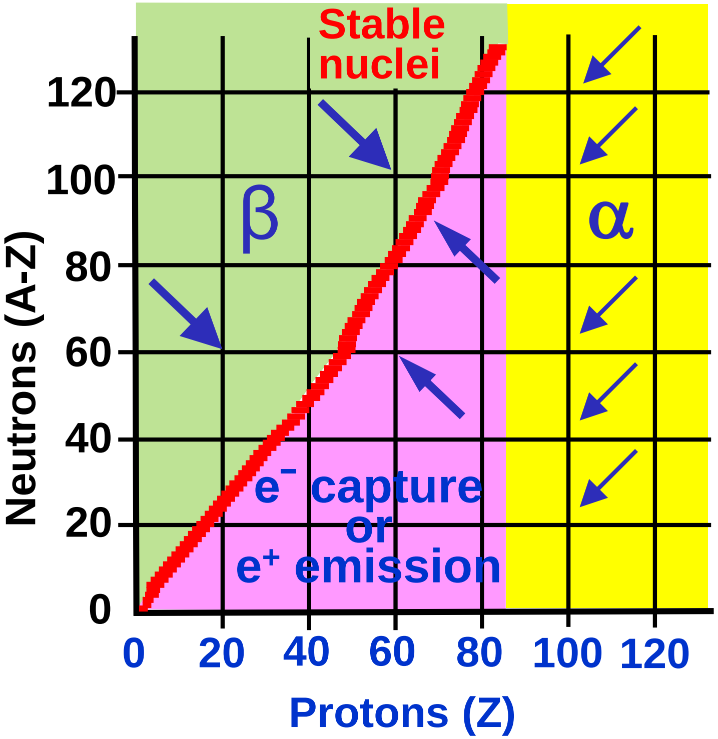
γ

γ Radiations (Futons)

very penetrants (v = c)

Nuclear Decay.

- **Why nuclides decay…**
  - They need of a stable ratio neutrons/protons



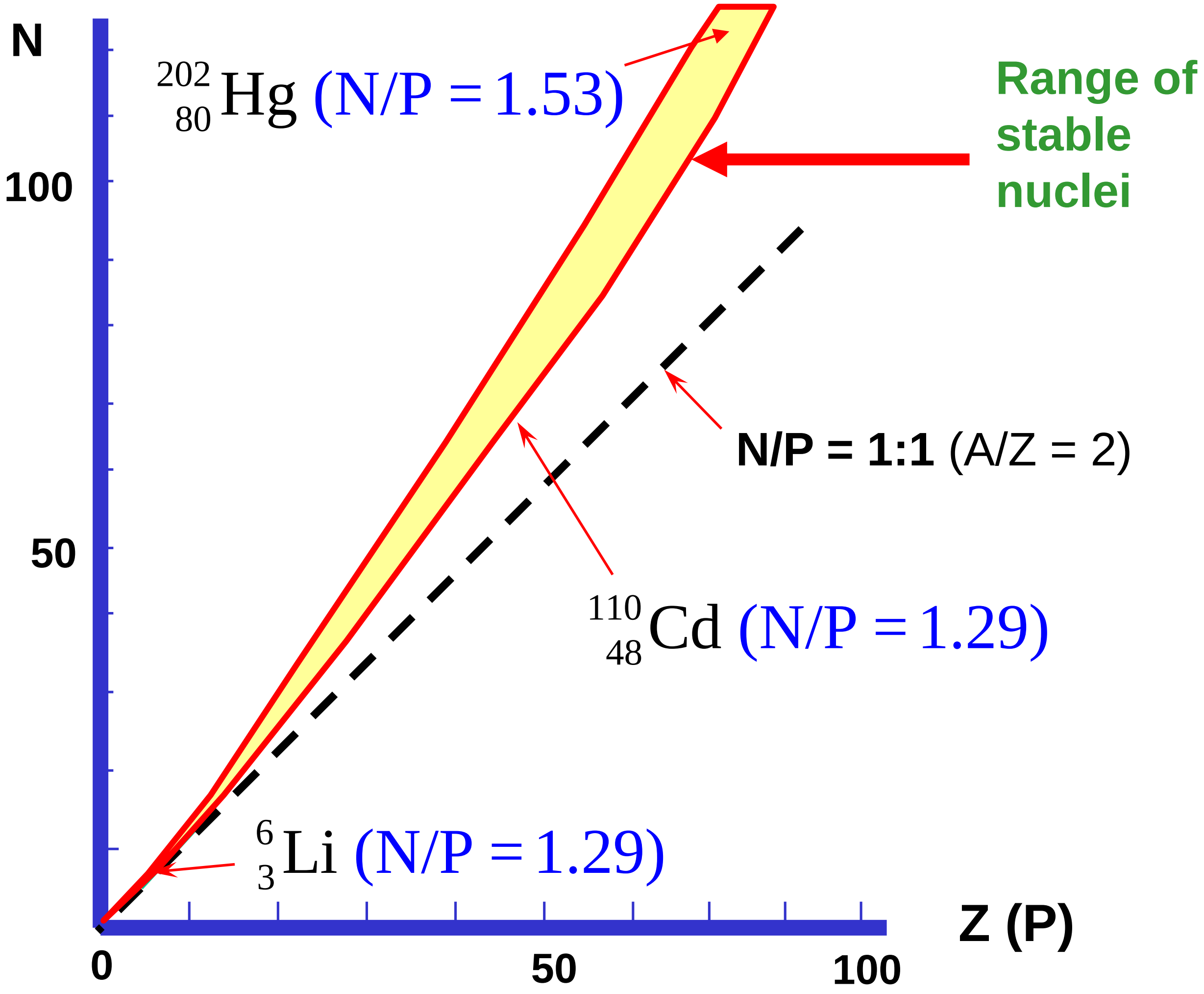
$$^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

$$^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\mathrm{e}$$

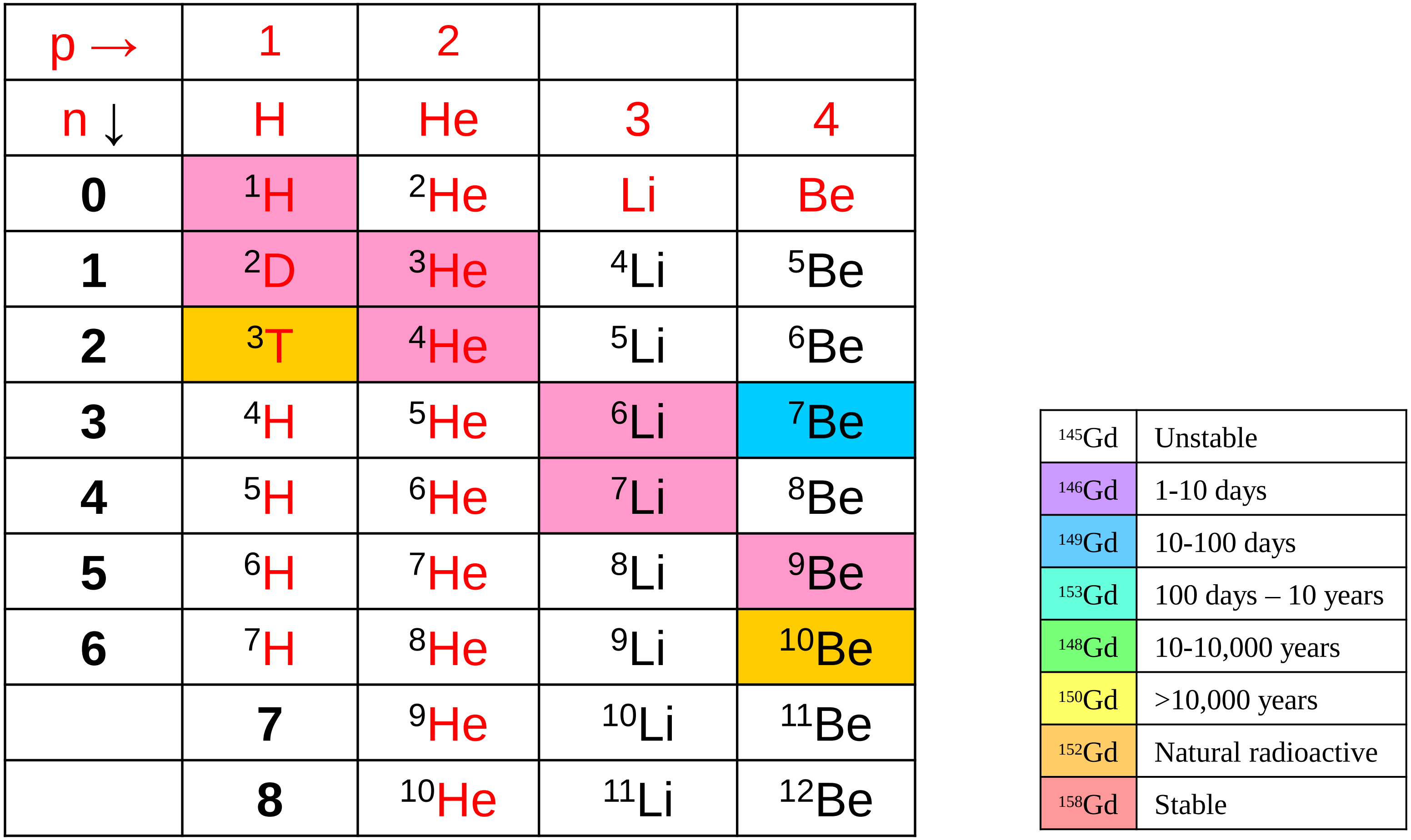
$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e}$$

$$^{106}_{47}\mathrm{Ag} + {}^{0}_{+1}\mathrm{e} \rightarrow {}^{106}_{46}\mathrm{Pd}$$

Trend in Nuclear Stability.



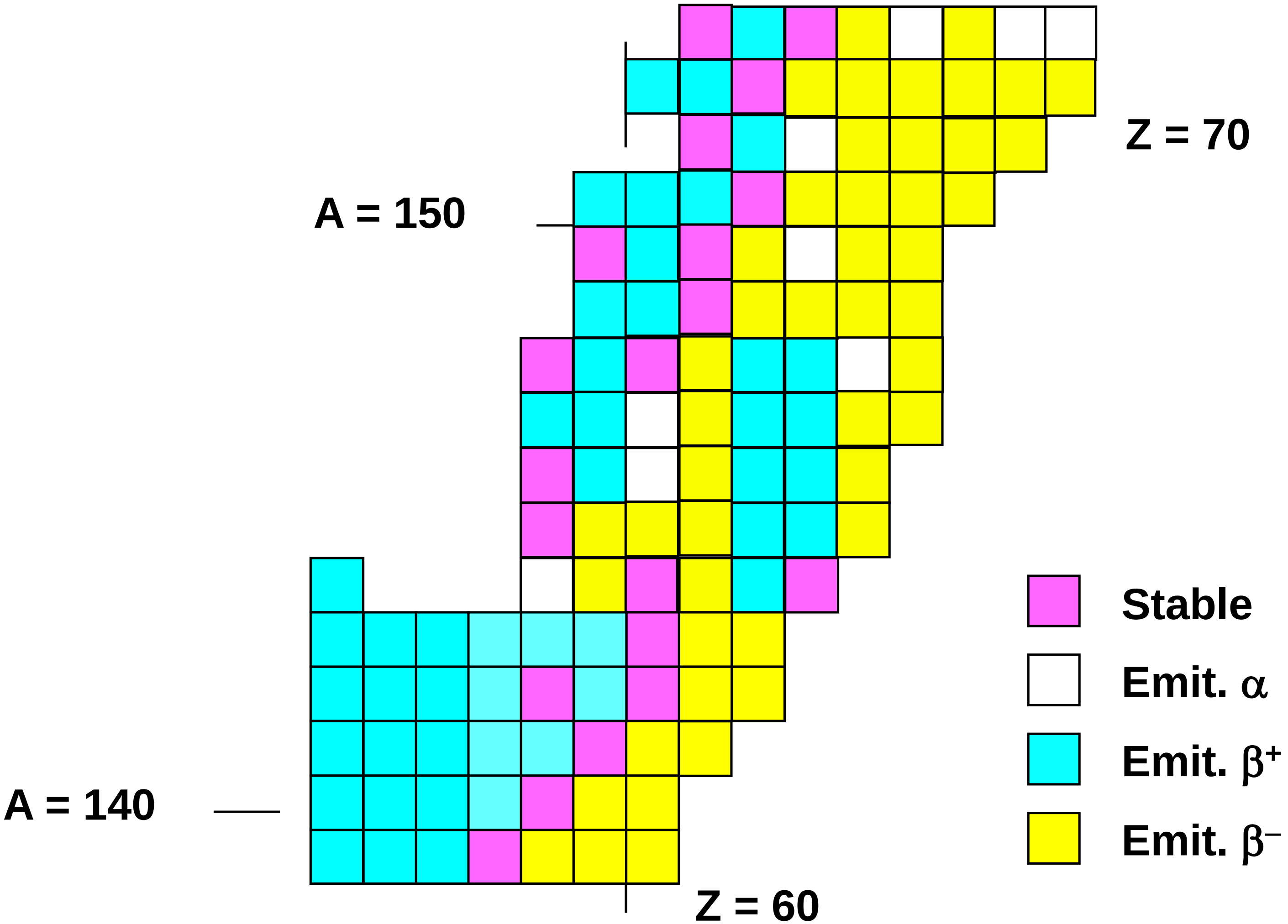
Trend in Nuclear Stability (2).



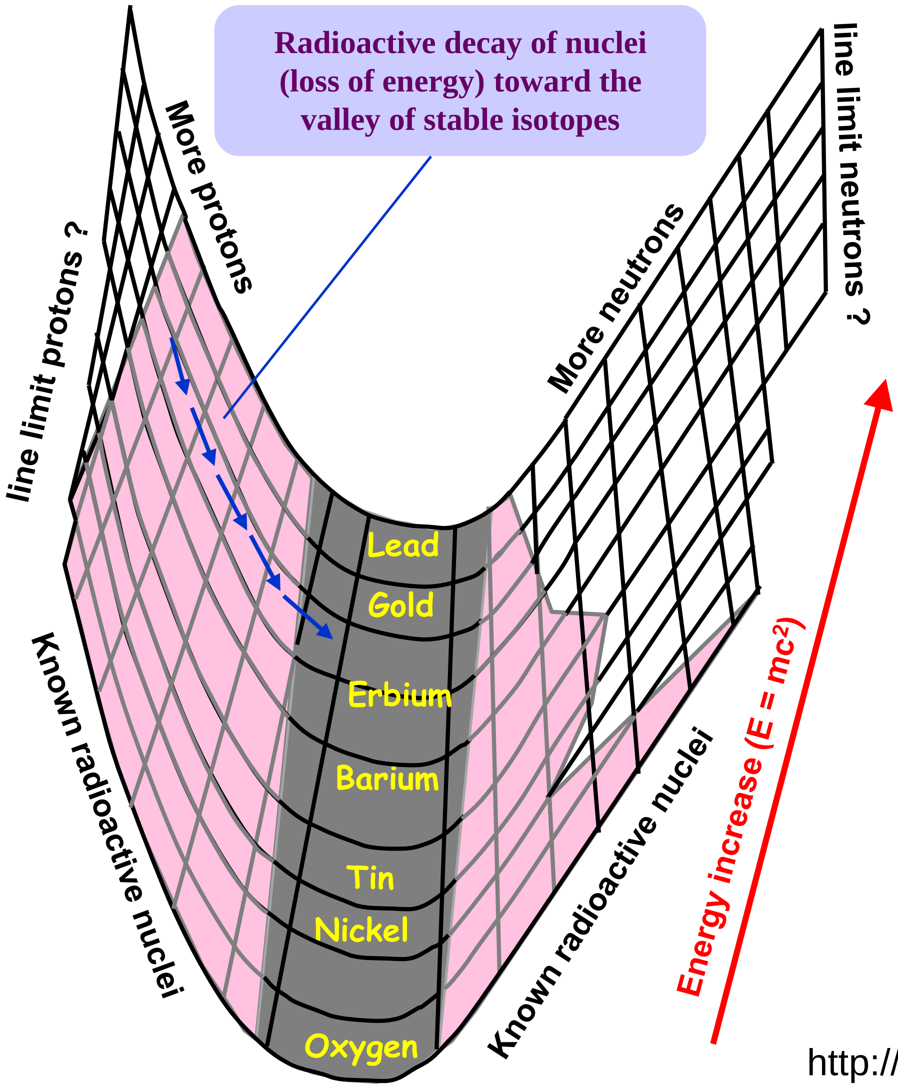
p →	1	2		
n ↓	H	He	3	4
0	^{1}H	^{2}He	Li	Be
1	^{2}D	^{3}He	^{4}Li	^{5}Be
2	^{3}T	^{4}He	^{5}Li	^{6}Be
3	^{4}H	^{5}He	^{6}Li	^{7}Be
4	^{5}H	^{6}He	^{7}Li	^{8}Be
5	^{6}H	^{7}He	^{8}Li	^{9}Be
6	^{7}H	^{8}He	^{9}Li	^{10}Be
	7	^{9}He	^{10}Li	^{11}Be
	8	^{10}He	^{11}Li	^{12}Be

^{145}Gd	Unstable
^{146}Gd	1-10 days
^{149}Gd	10-100 days
^{153}Gd	100 days – 10 years
^{148}Gd	10-10,000 years
^{150}Gd	>10,000 years
^{152}Gd	Natural radioactive
^{158}Gd	Stable

Trend in Nuclear Stability (3).



Trend in Nuclear Stability (4).



Radioactive decay of nuclei (loss of energy) toward the valley of stable isotopes

http://www.phy.ornl.gov/hribf/science/abc/

Natural and Artificial Radioactivity.

Natural Radioactivity

- Isotopes existing on earth owing to the evolution of our planet. Uranium
- Produced by cosmic rays coming from sun. Carbon-14

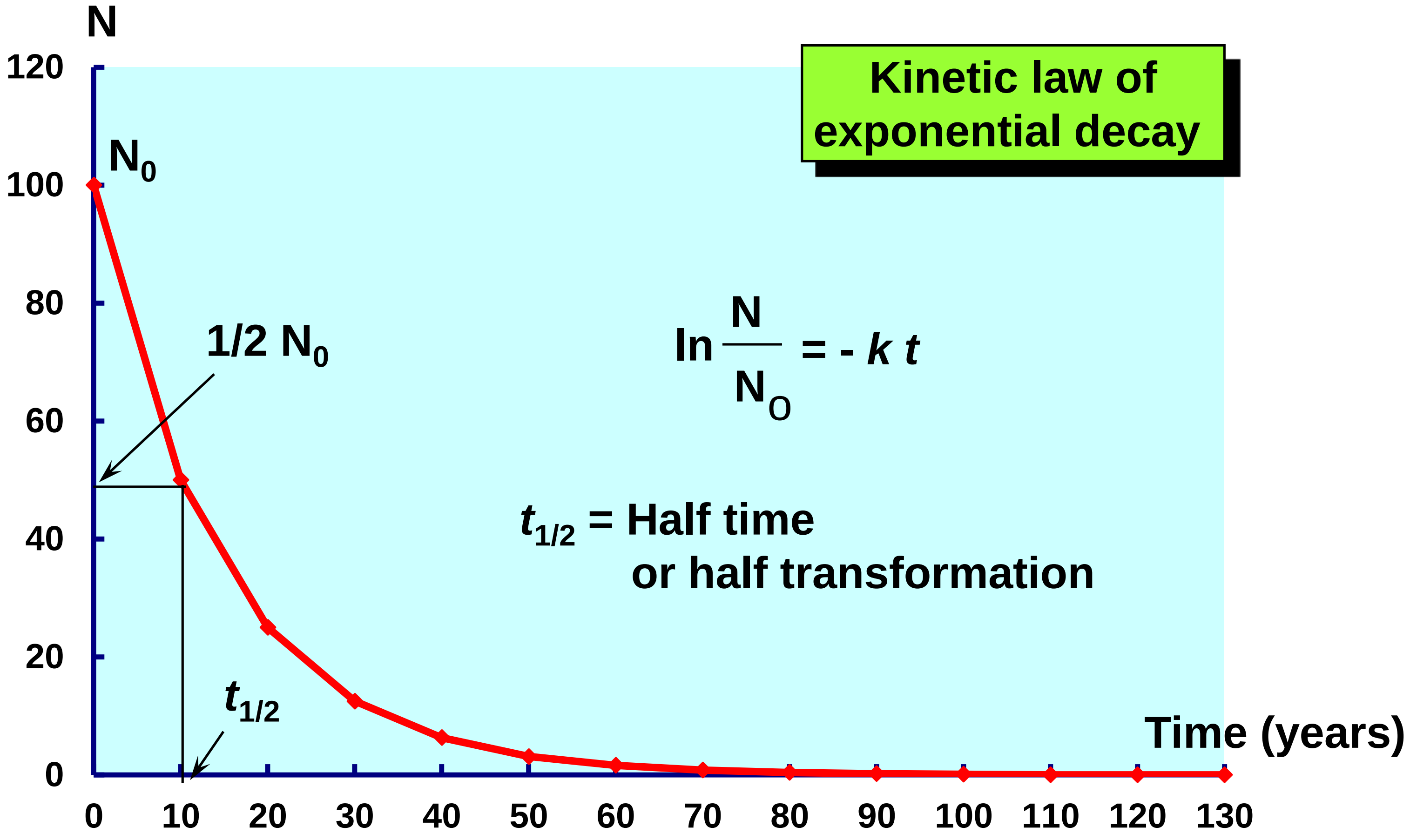
Artificial Radioactivity

- Obtained in nuclear reactions by fission or fusion of nuclei. Plutonium
- Produced using cyclotrons, linear accelerators, etc..

Examples of Half Life.

Isotope	Half life	Main Uses
Carbon-14	**5730 years**	Objects dating
Cobalt-60	**5.271 years**	Cancer treatment
Iron-59	**44.496 days**	Tracer, half life of red blood cells
Hydrogen-3	**12.26 years**	Biochemical Tracer
Iodine-131	**8.040 days**	Tracer, thyroid functionality
Potassium-40	**$1.25 \cdot 10^9$ years**	Rocks dating
Sodium-24	**14.659 hours**	Tracer, cardiovascular system
Uranium-238	**$4.51 \cdot 10^9$ years**	Rocks dating
Uranium-235	**$700 \cdot 10^6$ years**	
Plutonium-239	**24,000 years**	

Decay Kinetics and $t_{1/2}$.

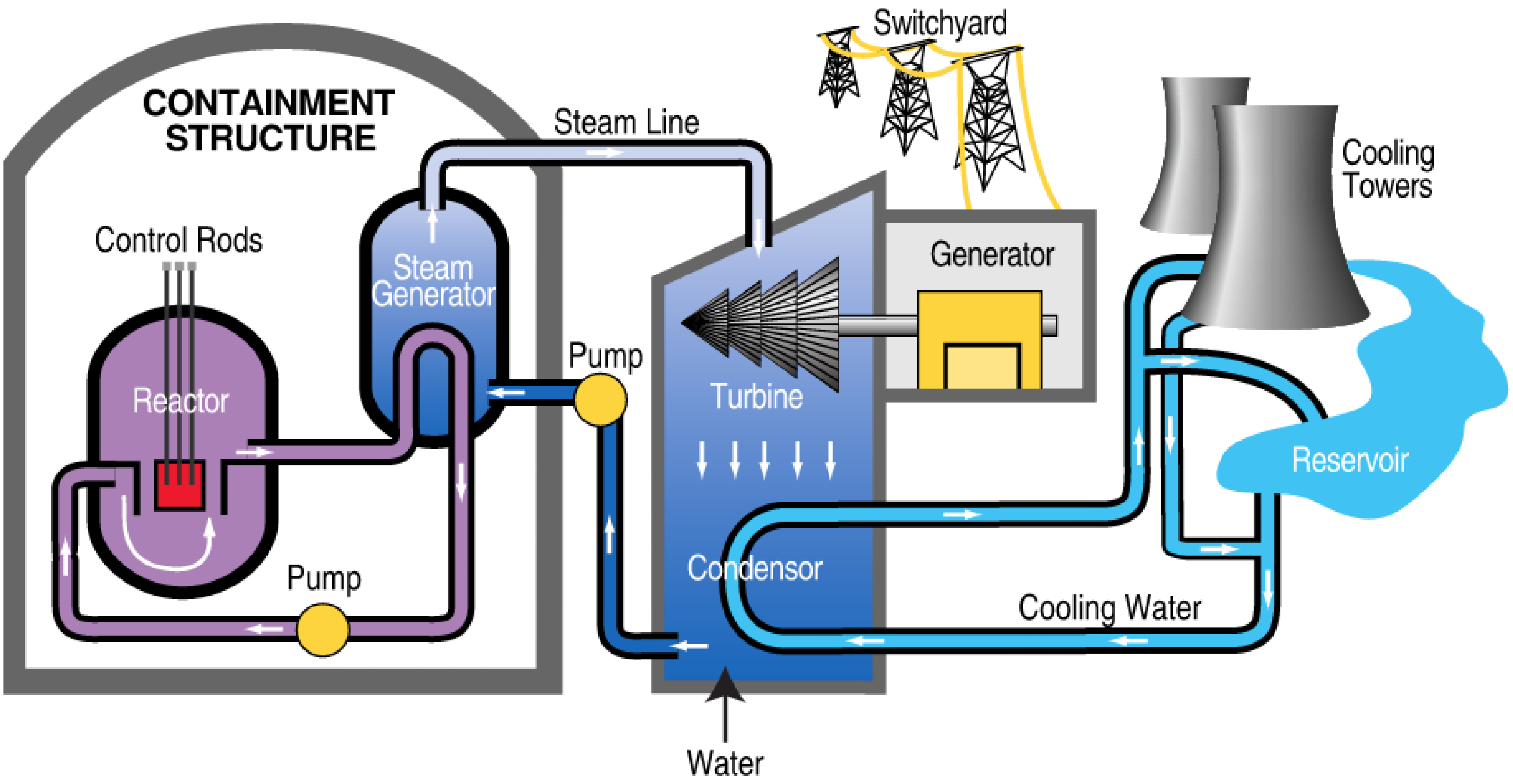


Kinetic law of exponential decay

$$\ln \frac{N}{N_O} = -\,k\,t$$

$t_{1/2}$ = Half time
or half transformation

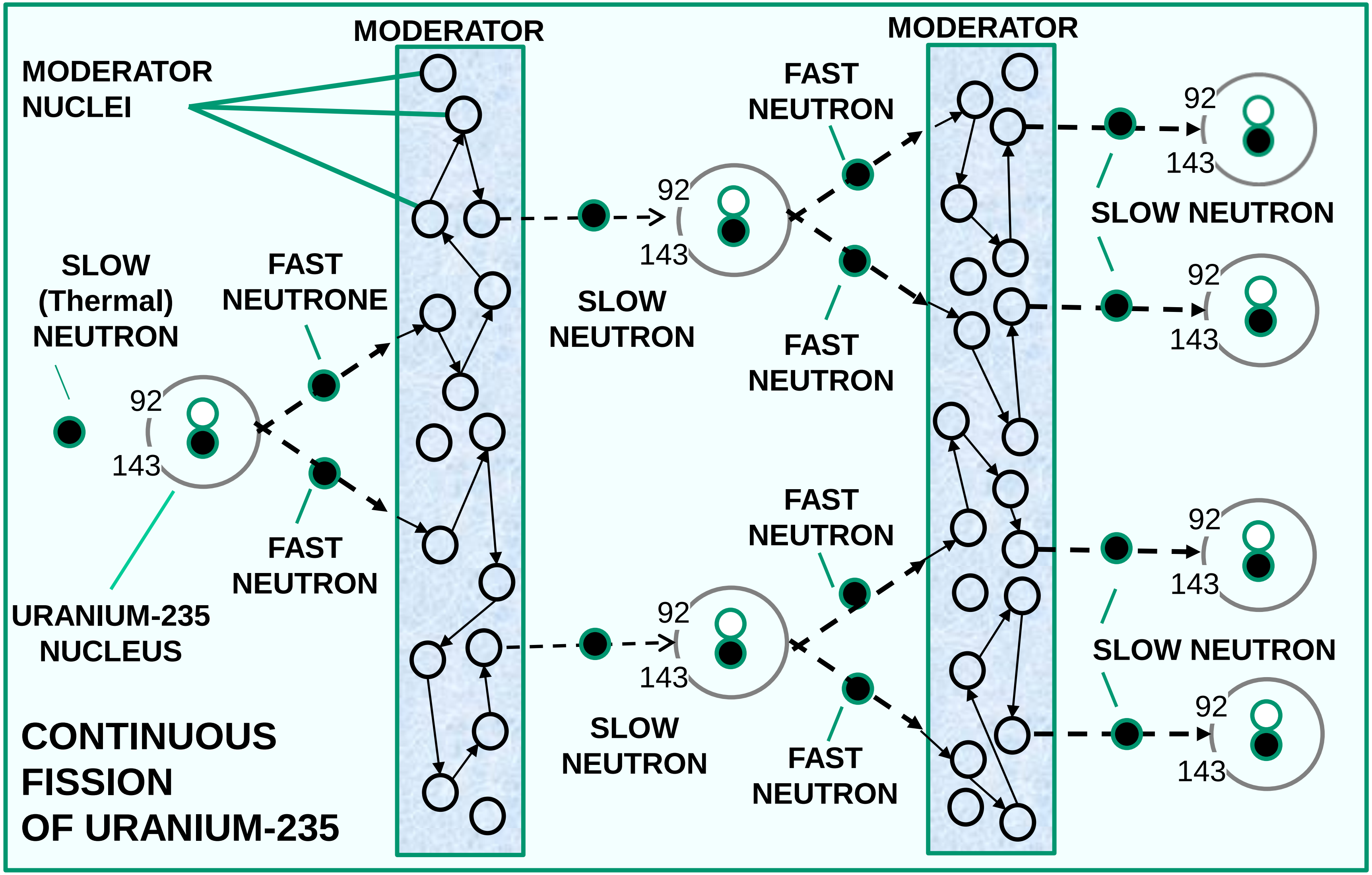
Nuclear Plant (Energy Taken out by Steam Turbine).



How a Nuclear Reactor works.

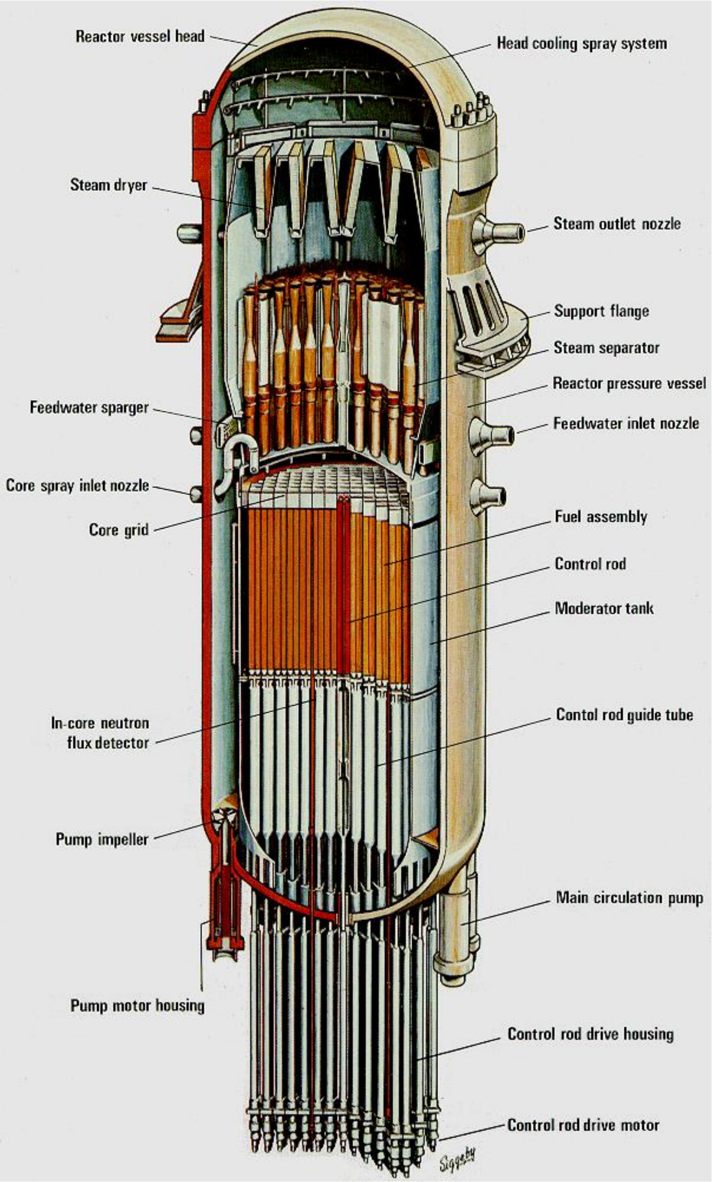
- ^{235}U fissions by absorbing a neutron and producing 2 to 3 neutrons, which initiate on average one more fission to make a controlled chain reaction
- Normal water is used as a moderator to slow the neutrons since slow neutrons take longer to pass by a U nucleus and have more time to be absorbed
- The protons in the hydrogen in the water have the same mass as the neutron and stop them by a billiard ball effect
- The extra neutrons are taken up by protons to form deuterons
- ^{235}U is enriched from its 0.7% in nature to about 3% to produce the reaction, and is contained in rods in the water
- Boron control rods are inserted to absorb neutrons when it is time to shut down the reactor
- The hot water is boiled or sent through a heat exchanger to produce steam. The steam then powers turbines.

Nuclear Fission from Slow Neutrons and Water Moderator.



Inside a Nuclear Reactor.

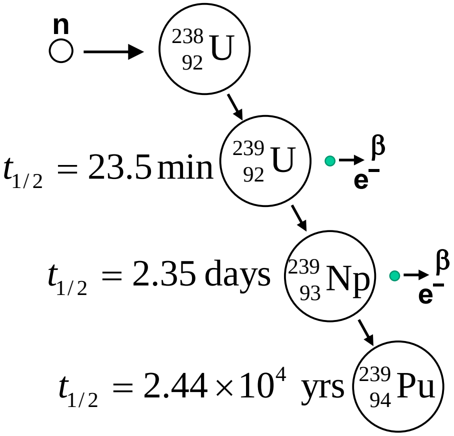
- Steam outlet →
- Fuel Rods →
- Control Rods →

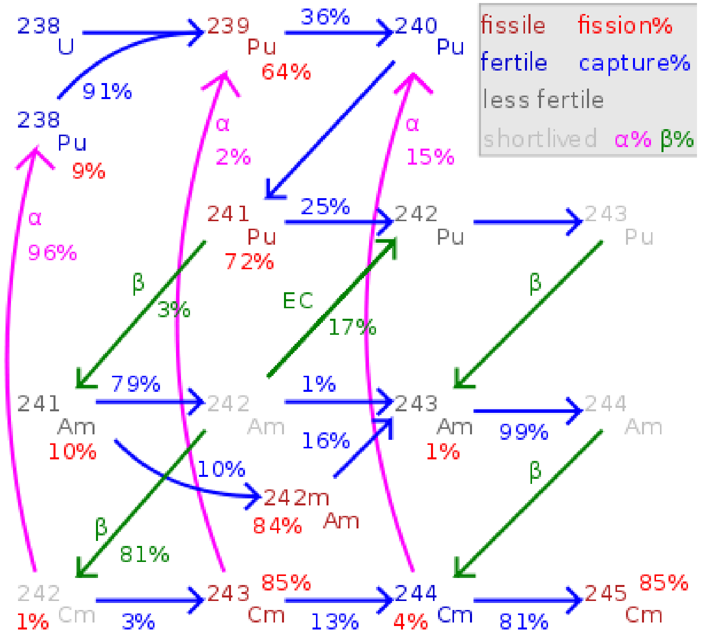


Production of Plutonium (Pu) in Nuclear Reactors.

- ^{239}Pu is produced in nuclear reactors by the absorption of a neutron on ^{238}U, followed by two beta decays
- ^{239}Pu also fissions by absorbing a thermal neutron, and on average produces 1/3 of the energy in a fuel cycle.
- ^{239}Pu is relatively stable, with a half life of 24 thousand years.
- It is used in nuclear weapons
- It can be bred for nuclear reactors

Conversion of ^{238}U to ^{239}Pu





Nuclear Problems and Solutions.

Three Mile Island 1979

- 50% core meltdown, stuck valve with no indicator released water, but containment vessel held
- More sensors added, better communication to experts in Washington, don’t turn off emergency cooling
- 28 year US safety record since accident

Chernobyl 1986

- Human stupidity turned off cooling system
- Poor steam cooling reactor design allowed unstable steam pocket to explode
- Graphite caught fire
- Design not used in other countries

Fukushima 2011

- After a tsunami the plant was heavily damaged
- Two reactors exploded
- Extensive contamination

Liquid Metal Fast Breeder Reactor.

- Uses the fast neutrons from ^{235}U fission on surrounding ^{238}U to produce ^{239}Pu
- In 10-20 years, enough Pu is produced to power another reactor
- No moderators are allowed
- No water, must use liquid sodium coolant
- U must be at 15%-30% enrichment to generate power with fast neutrons while breeding Pu
- This is at weapons grade enrichment, however
- Super-Phoenix in France has operated for 20 years

Nuclear Power Proposed Solution?

Richard Garwin , MIT and industry propose:
If 50 years from now the world uses twice as much energy, and half comes from nuclear power
Need 4,000 nuclear reactors, using about a million tons of Uranium a year
With higher cost terrestrial ore, would last for 300 years
Breeder reactors creating Plutonium could extend supply to 200,000 y.

Property of the source:

- Non-CO_2 producing source
- Need more trained nuclear engineers and sites
- Study fuel reprocessing, waste disposal, and safer designs.
- While nuclear reactors have to be on all day and night, and power use is less at night, they could be used to charge up electric cars.
- Until electric cars or a hydrogen generation economy, they might only be used for the 40% of generation used at night, up from the present 20% that they generate.

Fusion Reactors.

- Fusion easiest for Deuteron (D) + Tritium(T):

  $$D(p,n) + T(p,nn) \rightarrow {}^{4}He(pp,nn) + n$$

  in a high temperature plasma.
- Replacement T created from Li blanket around reactor

  $$n + {}^{6}Li \rightarrow {}^{4}He + T$$
- Fusion reactors
  - International ITER in 2012 for research for a decade, costing $5 billion
  - Current stalemate over siting in France or Japan
  - Followed by DEMO for a functioning plant, taking another 10 years.
  - Design and completion of a commercial plant not until 2050.
- US Lithium supply would last a few hundred years.
- Still would be a radioactive waste disposal problem.