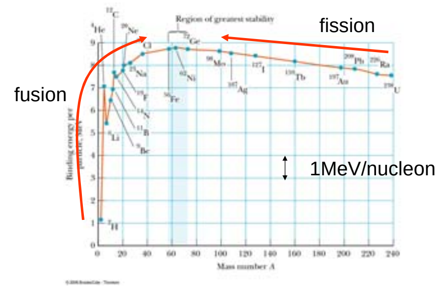
10.1 Nuclear energy

Nuclear Fission

Nuclear Fusion

Curve of the Binding Energy/nucleon



Energy can be released by nuclear reactions of Fusion and Fission

Natural radioactivity

Many elements found in nature are unstable and decay emitting radioactivity.

These include Uranium, ^{238}U , Radon ^{224}Ra and Potassium ^{40}K. Carbon ^{14}C,

The half lives of natural radio-isotopes are long.
Not useful as sources for power.
Low Power output.

Nuclear Power

- Nuclear power requires induced nuclear fission.
- Nuclear fission can be induced by neutrons in a chain reaction.
- Nuclear fusion can be induced by collisions at high temperature.

Induced Nuclear reactions

Can result in short half lives- fast reactions-high energy density

Combining nuclei (Fusion)

$$^{2}_{1}D + ^{2}_{1}D \longrightarrow ^{3}_{1}T + ^{1}_{1}H \quad + \text{Energy}$$

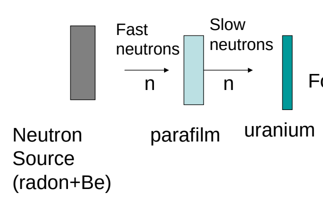
Neutron reactions (Fission)

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n \quad + \text{Energy}$$

Fission of Uranium

Bombard uranium with neutrons

Enrico Fermi (1936)



Found induced radioactivity

"Transuranium elements"

Fission of Uranium

Strassman and Hahn (1939)

Irradiated Uranium with neutrons
Detected Barium
Conclude Uranium nuclei splits into smaller fragments

$${}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{141}_{56}Ba + other\_products$$

Liquid Drop model-

Explained fission due to the instability of the higher larger nucleus.

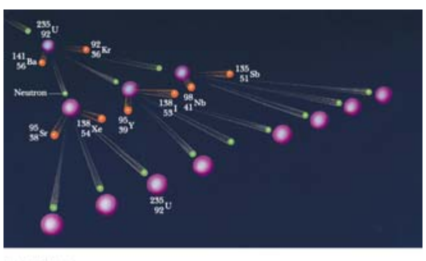
Lise Meitner

$T_{1/2}$ ~10^{-12} s

$${}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U \longrightarrow \text{Ba + products}$$

ΔE (average) =208 MeV

Nuclear Chain reaction



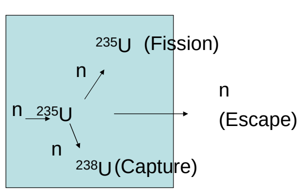
Chain Reaction
binding of 1 neutron releases ~3 neutrons
Each neutron can initiate another reaction

Two major isotopes of Uranium

^{235}U (0.7%) Fissionable upon neutron capture

^{238}U (99.3%) Non-Fissionable upon neutron capture

Critical Condition for Chain reaction



Nuclear reactor

Reproduction constant
K = no. of neutrons that produce a new fission event

K=1 (self –sustained reaction)

Enriched ^{235}U

Natural Uranium is a mixture of ^{235}U (0.7%) and ^{238}U(99.3%)

Most Uranium nuclear reactors use uranium enriched in ^{235}U. (2-3%)

Nuclear weapons used highly enriched ^{235}U. (~90%)

Enrichment done by mass separation.
- Gaseous diffusion
- Centrifuge process.
- Laser separation

Centrifuge separation of isotopes

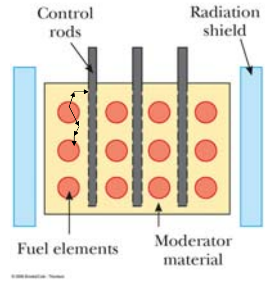
centrifugal separation gaseous UF_6

Nuclear reactor

fast neutrons must be slowed down to react efficiently.

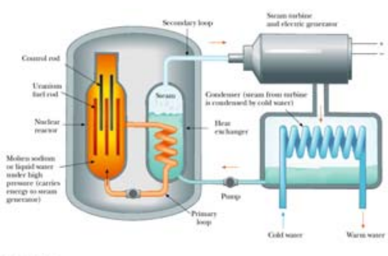
Moderator- slows neutrons to thermal velocities.

Control rods- neutron absorbers to control the level of neutrons



Critical condition. – When each neutron released initiates a new reaction.

Nuclear reactor



Plutonium

Plutonium is a fissionable material created in a nuclear reactor.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{94}Pu + 2e^{-}$$

^{239}Pu can be made into nuclear bombs.

Pu can be chemically separated from U in spent fuel rods from nuclear reactors.

Question

How many gallons of gasoline ($1.3x10^8$ J of energy/gallon) would be equivalent to a kg of Uranium? ΔE=208MeV

No. of fissionable nuclei =N

$$N = (fraction^{235}U)(\frac{m}{mass/atom}) = (0.0072)\left[\frac{1kg}{238u(1.66x10^{-27}kg/u)}\right] = 1.8x10^{22}$$

Energy released = E = N(ΔE)

$$E = N(\Delta E) = 1.8x10^{22}(208x10^{6}eV)\left[1.6x10^{-19}J/eV\right] = 6x10^{11}J$$

gallons of gasoline =V= $\frac{E}{E/gallon}$

$$\frac{E}{E/gallon} = \frac{6x10^{11}J}{1.3x10^{8}J/gallon} = 4.6x10^{3}gallons$$

Nuclear Fusion

Fusion of small nuclei releases energy

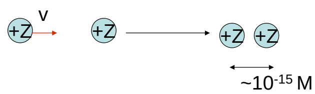
$$^{2}_{1}D + ^{2}_{1}D \longrightarrow ^{3}_{2}He + ^{1}_{0}n \qquad \Delta E= 3.27\ MeV$$

$$^{2}_{1}D + ^{2}_{1}D \longrightarrow ^{3}_{1}T + ^{1}_{1}H \qquad \Delta E= 4.03\ MeV$$

$$^{2}_{1}D + ^{3}_{1}T \longrightarrow ^{4}_{2}He + ^{1}_{0}n \qquad \Delta E=17.6\ MeV$$

Nuclear Fusion

High energy required to bring charged nuclei close together



Requirements for fusion
High Temperatures (T~ 10^8 K)

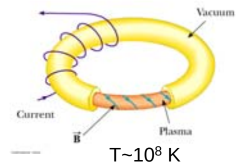
High density (n) for long time (τ)

Lawson Criterion

$n\tau > 10^{14}$ s/cm^3

Plasma Fusion
Magnetic Confinement

Plasma is a gas of ionized atoms
Heated to high temperature
Confined by magnetic forces

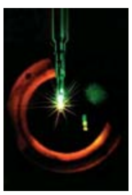


T~10^8 K

Princeton Tokomak

long times
low density

Laser fusion-
Inertial Confinement



Deuterium pellet
is heated by a short
laser pulse

Lawrence Livermore Lab
Nova Laser

Short times
High density

Prospects

- Nuclear energy by fission is currently a source of much of the electrical power (~15% USA).
- The problems with nuclear energy
  - Radioactive waste disposal
  - Atomic bomb threats
  - Easily mined U is limited (~100 yr supply)
- Nuclear fusion reactions promise an unlimited source of energy.
  - Controlled fusion reactions are not yet possible.