Example : fusion of Deuterium & Tritium

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{1}He + {}^{1}_{0}n$$

Calculate total binding energy before and after

Before :

${}^{2}_{1}H$	2 × 1.112 MeV/nucleon
${}^{3}_{1}H$	3 × 2.827 MeV/nucleon
Total :	10.705 MeV

After

${}^{4}_{2}He$	4 × 7.074	
${}^{1}_{0}n$	1 × 0	(neutron is free)
total :	28.296	

Difference : **17.59 MeV**

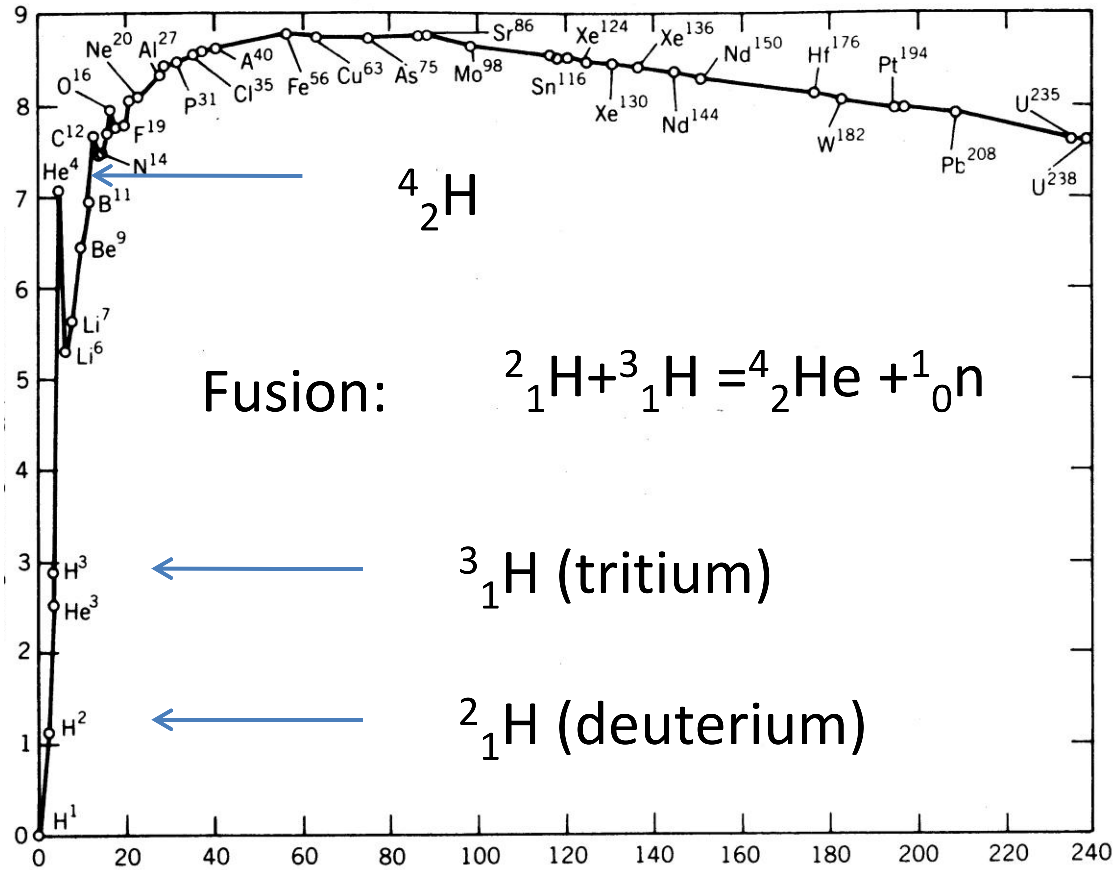
This is the amount of energy released by fusing deuterium & tritium nuclei

Problem : it is hard to overcome the repulsion of the protons

∴ Impractical at present.

Data from Table 10-4

Nuclear Binding Energy vs. Mass Number



Binding energy per nucleon (MeV)

$^{4}_{2}H$

Fusion: $^{2}_{1}H + ^{3}_{1}H = ^{4}_{2}He + ^{1}_{0}n$

$^{3}_{1}H$ (tritium)

$^{2}_{1}H$ (deuterium)

Number of Nucleons (A=Z+N)

Fusion reaction gains binding energy

Fission

Ex $^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{95}_{38}Sr$

Before $235 \times 7.59 \frac{MeV}{nucleon}$

Total : 1783.65 MeV

After $140 \times 8.295 = 1161.3$ MeV

$95 \times 8.552 = 812.44$ MeV

Total : 1973.74 MeV

Net difference (final - initial)

= 190.1 MeV

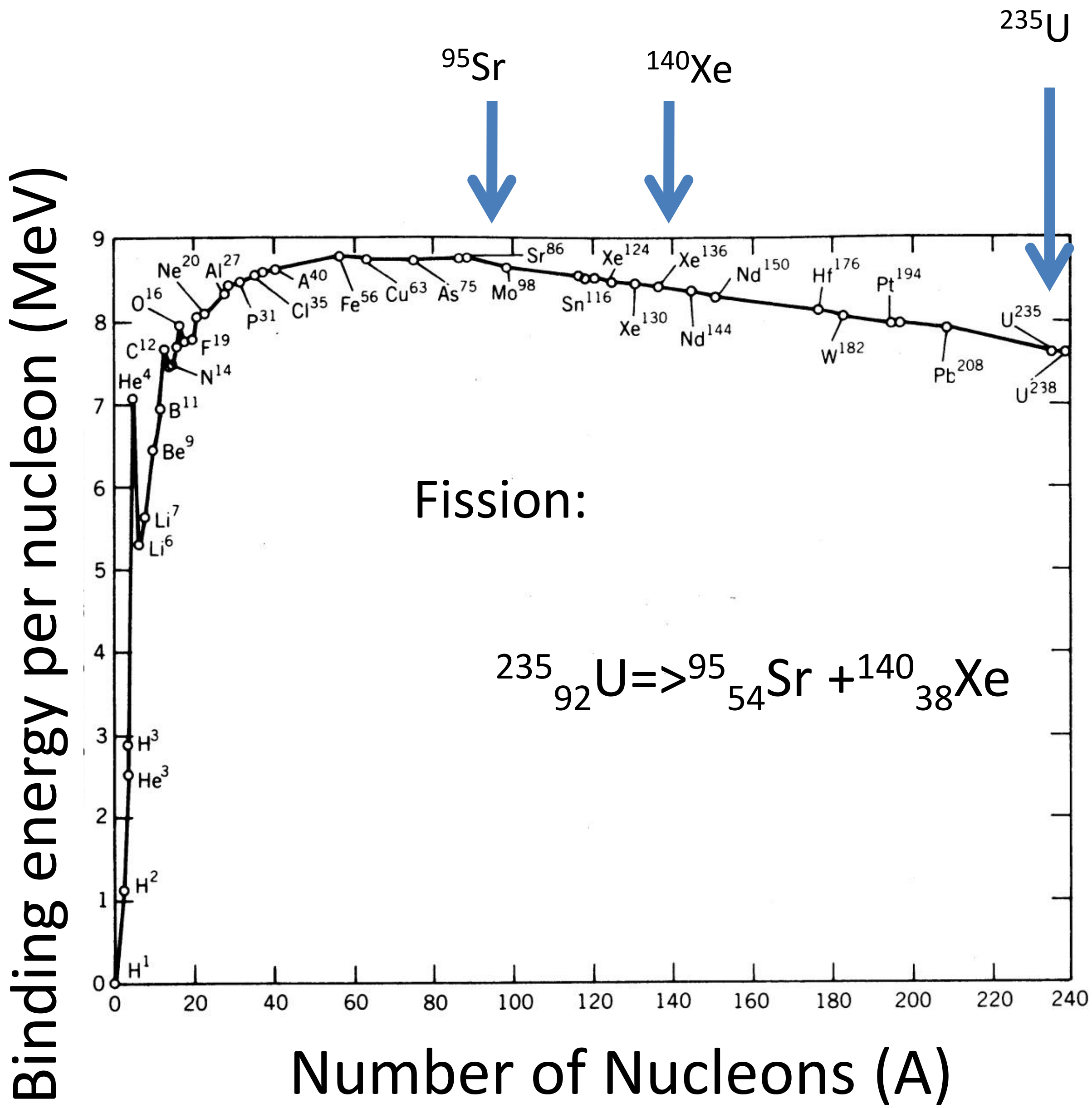
larger binding energy of final state

⇒ 190.1 MeV was released as kinetic energy ⇒ heat

Above is "spontaneous fission"

very low probability

Nuclear Binding Energy



Induced Fission :

This is the process used in most nuclear reactors :

2 step process :

<u>1st Step</u> : Neutron capture

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U$$

↑ unstable

BE = 1784 MeV   BE = 1791 MeV

Extra 7 MeV of energy causes internal excitation of ^{236}U making it unstable against <u>fission</u>

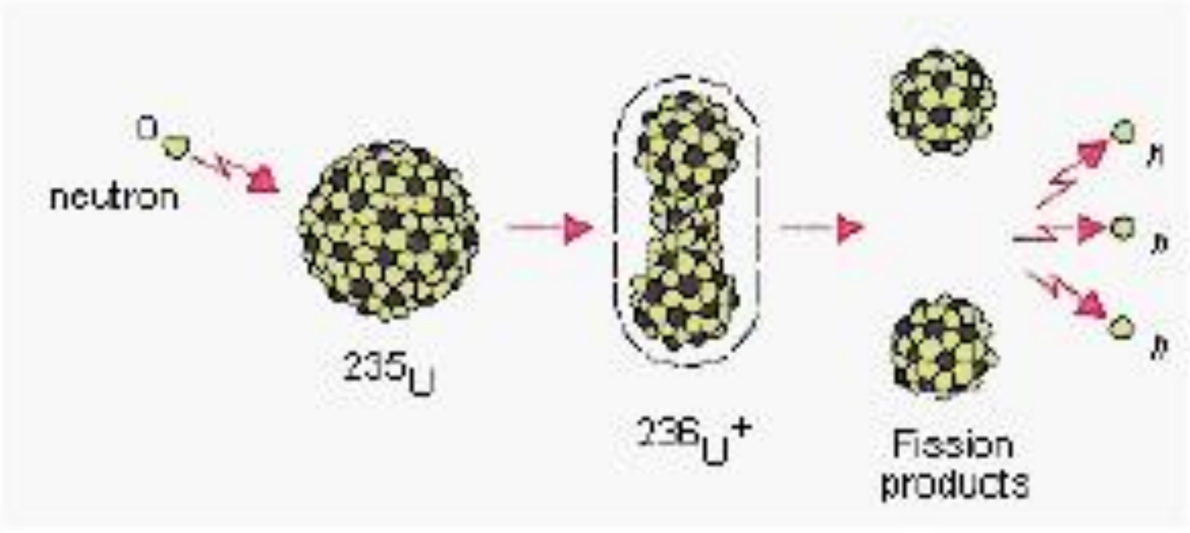
See Figure (next page)

<u>2nd Step</u> Excited $^{236}_{92}U$ nucleus decays into 2 nuclei

Induced Nuclear Fission

Spontaneous fission of ^{235}U is very rare

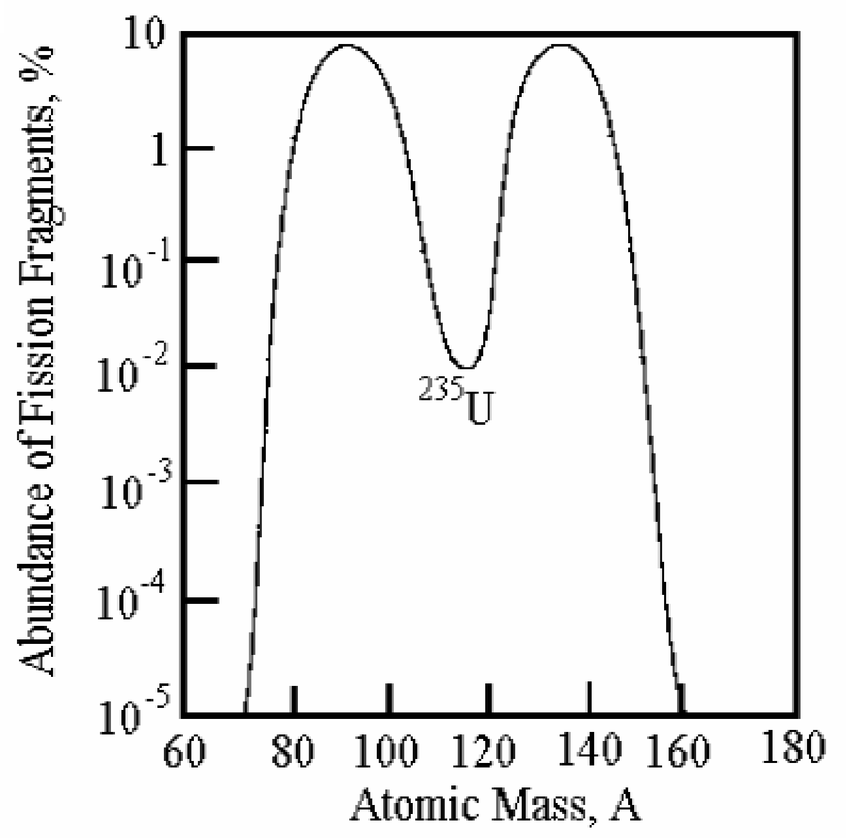
Induced fission is much more probable:



$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U} \rightarrow X + Y + qn$$

This is the type of process that is used in nuclear power generation

^{236}U Fission Fragment Distribution



^{236}U fission results in many different mass products

The mass distribution is “bimodal” i.e. double peaked

Energy released in a single ^{235}U Fission:

Decay Channel:	Energy
Fission fragment kinetic energies	170 MeV
KE of 2-3 neutrons emitted	5 MeV
Prompt γ-rays (~5 gammas)	6 MeV
~7 β particles	8 MeV
Fission fragment decay-antineutrinos	12 MeV
Fission fragment decay: γ-rays	6 MeV
Total energy released per ^{238}U fission: (excluding antineutrinos)	~200 MeV

Adapted from McFarland, Ch. 10

Bottom line ~200 MeV of energy available per ^{235}U fission
All of this is available as heat

Comparison of ^{235}U fission vs. fossil fuels

How many kg of coal are required to provide the energy in 1 kg of natural uranium?

Number of atoms of ^{235}U in 1kg:

Natural uranium contains 0.72% ^{235}U

1kg of natural uranium contains 0.0072 kg ^{235}U

Number of ^{235}U atoms = (.0072 kg/0.235 kg mol^{-1})x(6.022×10^{23} atoms mol^{-1})= 1.845×10^{22} atoms

Total energy released: =1.845×10^{22} atoms)x(200x10^{6}eV)x(1.60×10^{19} J/eV) = 5.9×10^{11} J

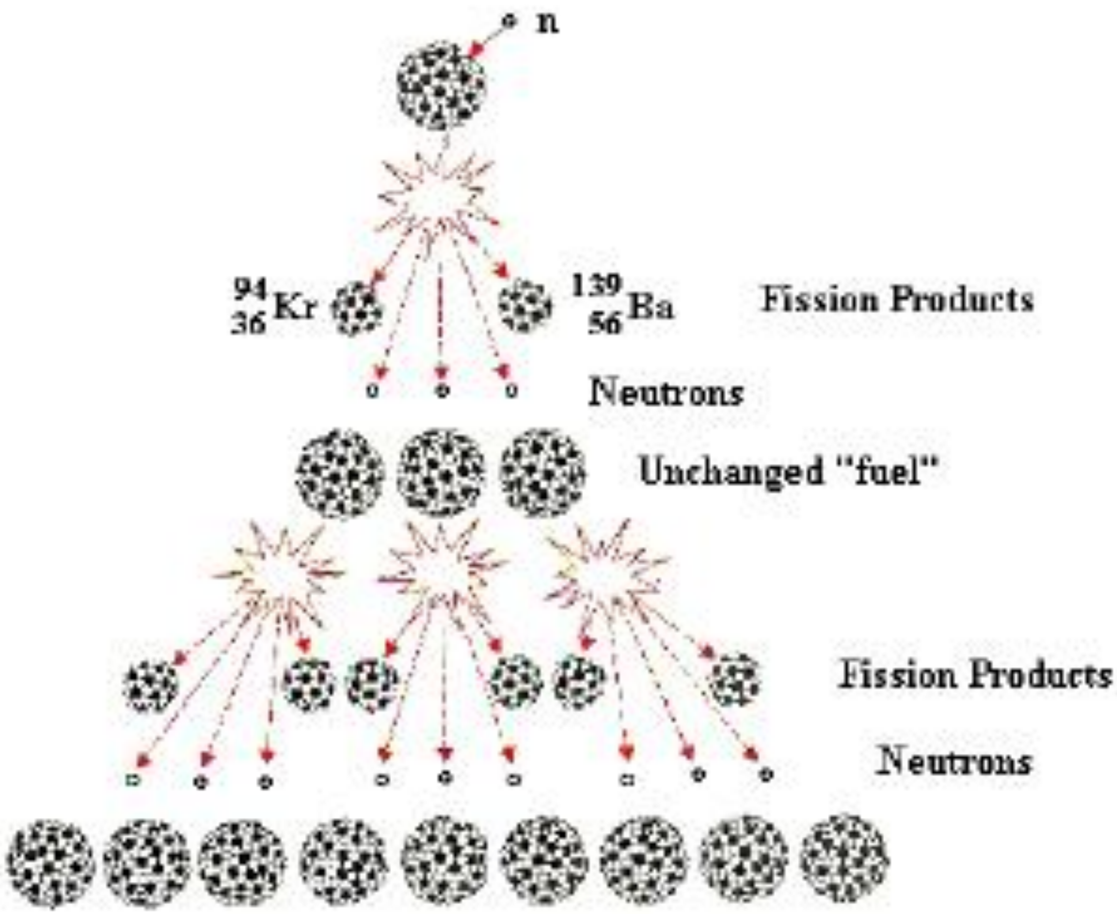
Therefore specific energy of natural uranium = 5.9×10^{11} J/kg.

Specific energy of coal: 2.34×10^{7} J/kg

Amount of coal needed to release 5.9×10^{11} J:

=(5.9×10^{11} J)/(2.34×10^{7} J/kg) = 2.52×10^{4} kg = 25 metric tons of coal!

Nuclear Chain Reaction

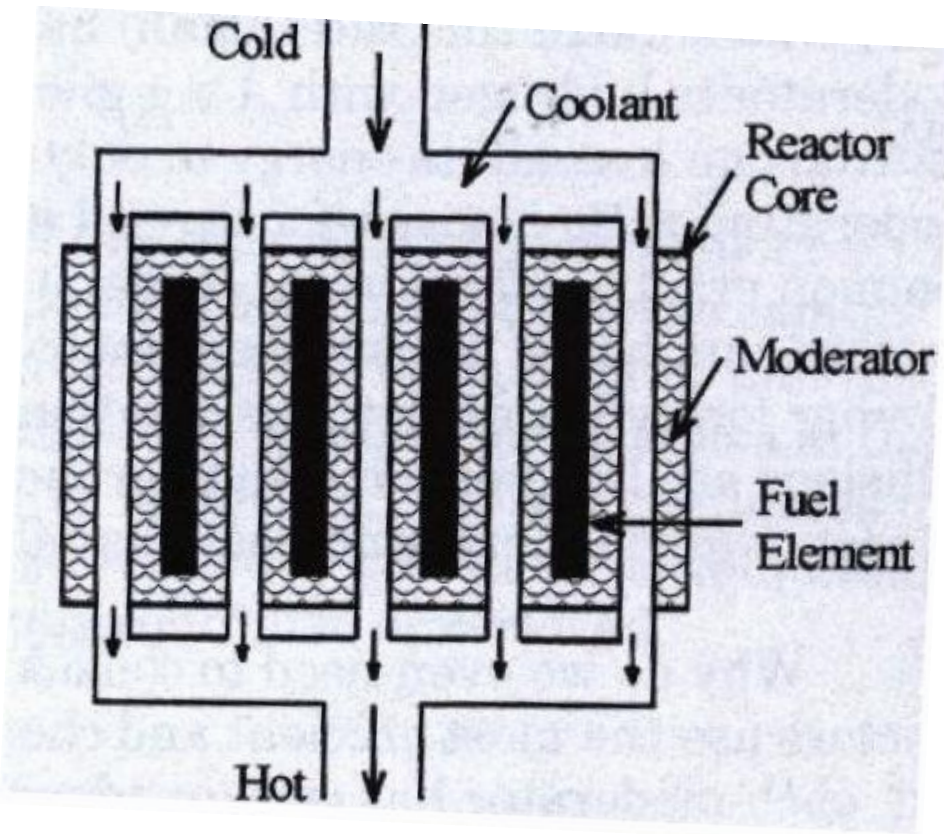


- One fission is not enough.
- We need a substantial number of fissions to generate power
- In a reactor core we need to build up a significant number of fissions per unit time.

Problem:
Neutrons must be slowed in order to let them react with the ^{235}U nuclei

Basic Nuclear Reactor Operation

A nuclear reactor is just a source of heat for a conventional steam cycle power plant.



From McFarland

Three critical components:

Fuel (currently primarily ^{235}U)

Moderator: needed to slow neutrons to allow fission to occur

Coolant: used to extract heat for power generation and to prevent fuel from overheating . In water moderated reactors, the water is also the coolant

Moderator

•Neutrons produced by fission have large energies (several MeV)

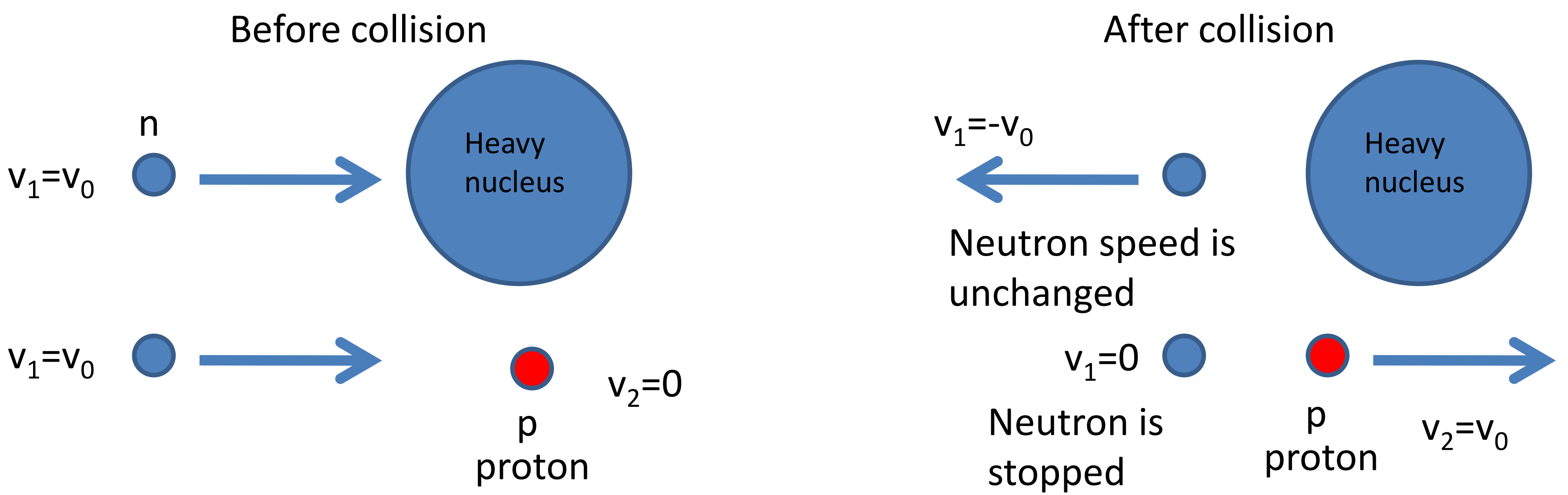
•Emitted neutrons need to be thermalized (slowed) to energies of order kT (0.03eV) so that they may be captured by other nuclei.

•A moderator serves is a material that is used to slow down the fast neutrons so that they can be used to initiate more fissions

•Neutrons lose energy primarily by elastic collisions with other nuclei.

•The most effective collisions are with objects with the same mass as a neutron, e.g. hydrogen:

Large nuclei do not slow neutrons:



Common moderator materials

Preceding slide leads us to conclude that hydrogen is the best moderator. Below are the three most commonly used moderators

Nucleus	Common Form	Ratio	No. of Collisions to Thermalize
Hydrogen	water	0	19
Deuterium	heavy water	0.11	32
Carbon	graphite	0.72	110

Obviously water is the best choice but there are other factors that have to be considered

- Most reactors worldwide use water as the moderator and coolant (high proton density)
- Canadian design (CANDU) uses D_2O (heavy water as moderator and coolant
- Graphite is used a moderator in notable cases (Chernobyl) in conjunction with air coolant.

Tradeoffs in moderator choice:

H_2O (Most of world's reactors)
•good moderator,
•good coolant,
•high cross section for neutrons
•enriched uranium must be used (expensive)

D_2O (Candu reactors)
•good moderator,
•good coolant,
•much lower cross section for neutrons
•heavy water is expensive to produce (isotope enrichment)
•natural uranium can be used (much cheaper than enriched fuel)

Graphite (Chernobyl)
•OK moderator,
•need to use additional cooling medium such as gas
•lower cross section for neutrons