Nuclear Energy

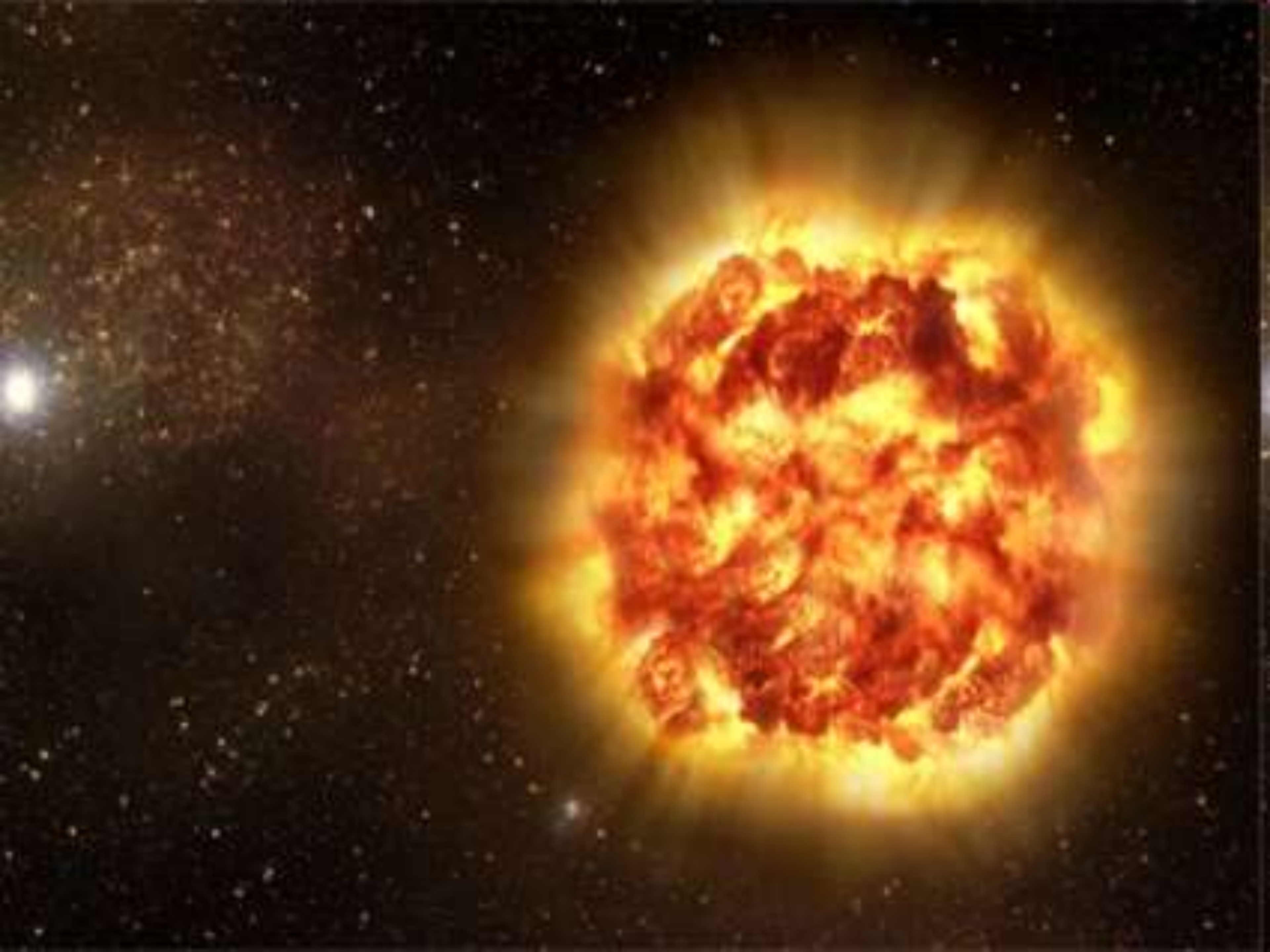
Nuclear fission

it is a disintegration process, in which a heavier nucleus gets split up into two lighter nuclei, with the release of a large amount of energy .

General fission reaction for U^{235}

$${}_{0}n^{1} + {}_{92}U^{235} \rightarrow {}_{92}U^{236} \rightarrow X + Y + \text{neutrons} + Q$$

X and Y are fission products. No. of neutrons released depends on the fission products. Q- disintegration energy



Fission fragments of $_{92}U^{235}$

i. $_{47}Ag^{113} + {}_{45}Rh^{120} + 3n + Q_1$.

ii. $_{44}Ru^{115} + {}_{48}Cd^{118} + 3n + Q_2$.

iii. $_{54}Xe^{140} + {}_{38}Sr^{94} + 2n + Q_3$.

iv. $_{56}Ba^{141} + {}_{38}Kr^{92} + 3n + Q_4$.

1. Silver + Rhodium
2. Ruthenium + Cadmium
3. Xenon + Strontium
4. Barium + krypton.

Total mass of fission fragments is less than total mass of uranium and neutron. Mass defect appear as energy Q

(Q ≈200MeV per disintegration).

Fission fragments are β – active

- **Fission of heavy elements 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).**
- **For fission to produce energy, the total binding energy of the resulting elements has to be higher than that of the starting element.**
- **Fission is a form of nuclear transmutation because the resulting fragments are not the same element as the original atom.**

Energy released by 1kg of U^{235} in kWh?

Energy released by one atom = 200 MeV

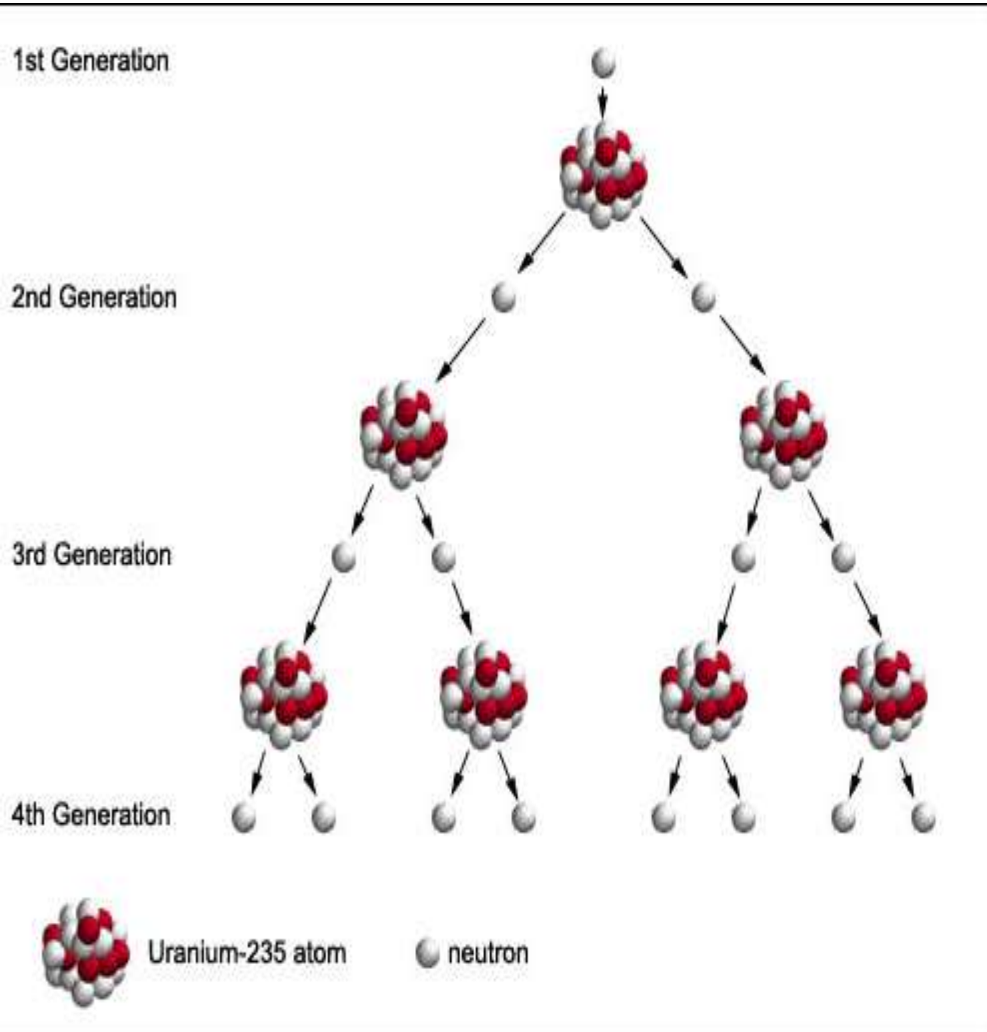
No. of atoms in 1kg = $N/235 \times 10^{-3}$

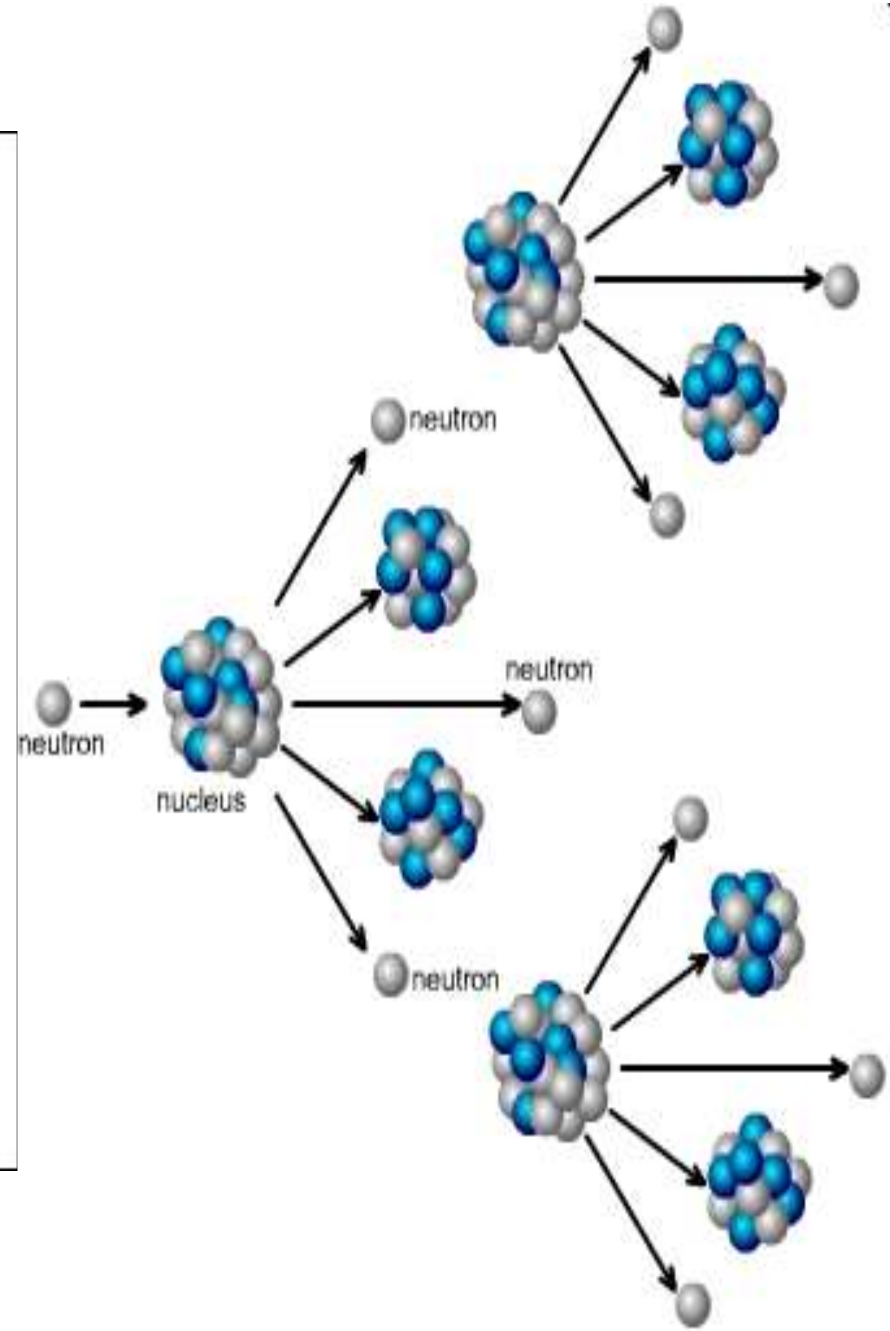
Total energy released = 2.26×10^{7} kWh

Chain reaction

A self propagating process in which number of neutrons goes on multiplying rapidly almost in geometrical progression during fission till whole of fissile material is disintegrated.

3 neutrons in the first fission trigger 3 uranium nuclei producing 9 neutrons which produce 27 neutrons and so on.


1st Generation
2nd Generation
3rd Generation
4th Generation
Uranium-235 atom
neutron


neutron
nucleus
neutron
neutron
neutron

Neutrons no. in n generation is 3^n.

Ratio of secondary neutrons produced to original neutrons is called multiplication factor (k)

k = 1 , fission is critical or steady

K>1 supercritical or building up

K<1 subcritical or dying down

Average of 2.5 neutrons/ fission .

1kg U^{235} contains ≈ $25x10^{23}$ atoms.

Capture of $_0n^1$ by U takes 10^{-8}sec.

No. of stages($2.5^n = 25 \times 10^{23}$) n ≈ 60 .

Time reqd for 60 fission = 0.6μs

Energy released / fission = 200MeV

Tot.E released = $200 \times 25 \times 10^{23}$

= $5x10^{26}$MeV

1g uranium fission = 2500kg of coal

Factors inhibit sustained chain reaction

i. Leakage of neutrons from the system

ii. Absorption of neutrons by non – fissionable materials (impurities).

iii. Absorption of neutrons by U^{238} .

ii. Minimised by purifying the fissionable material.

iii. Natural Uranium has 3 isotopes 238(99.28%) 235(0.714%) and 234 (0.006%). Since 235 very less, probability of collission with 238 is more. Though fast neutrons can cause fission in 238 , there is a greater probability of absorption of neutrons by U238,which reduces the chance of continuing chain reaction .

Critical size

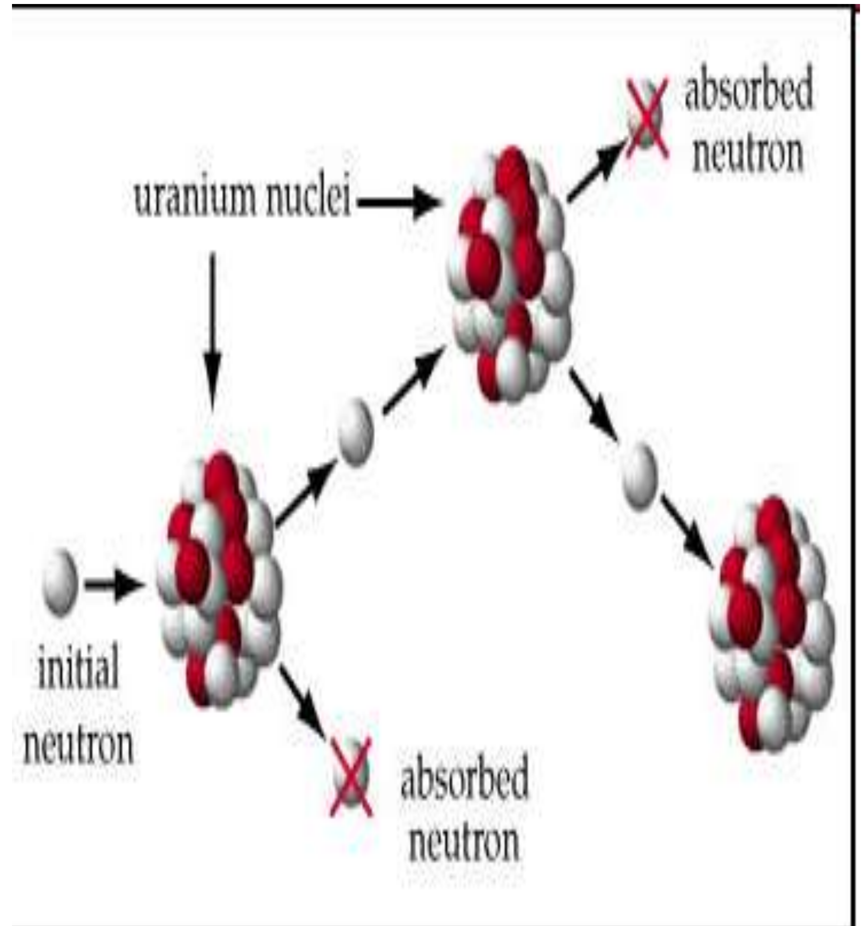
Minimum size of the fissile material for sustained fission reaction in which no. of neutrons produced in the fission process just balance those lost by leakage and non fission capture.

If the size is less than the critical size , chain reaction is not possible.

CONTROLLED CHAIN REACTION

- To maintain a sustained controlled nuclear reaction, for every 2 or 3 neutrons released, only one must be allowed to strike another uranium nucleus.
- If this ratio is less than one then the reaction will die out; if it is greater than one it will grow uncontrolled (an atomic explosion).
- A neutron absorbing element (control rods eg B or Cd)must be present to control the amount of free neutrons in the reaction space.

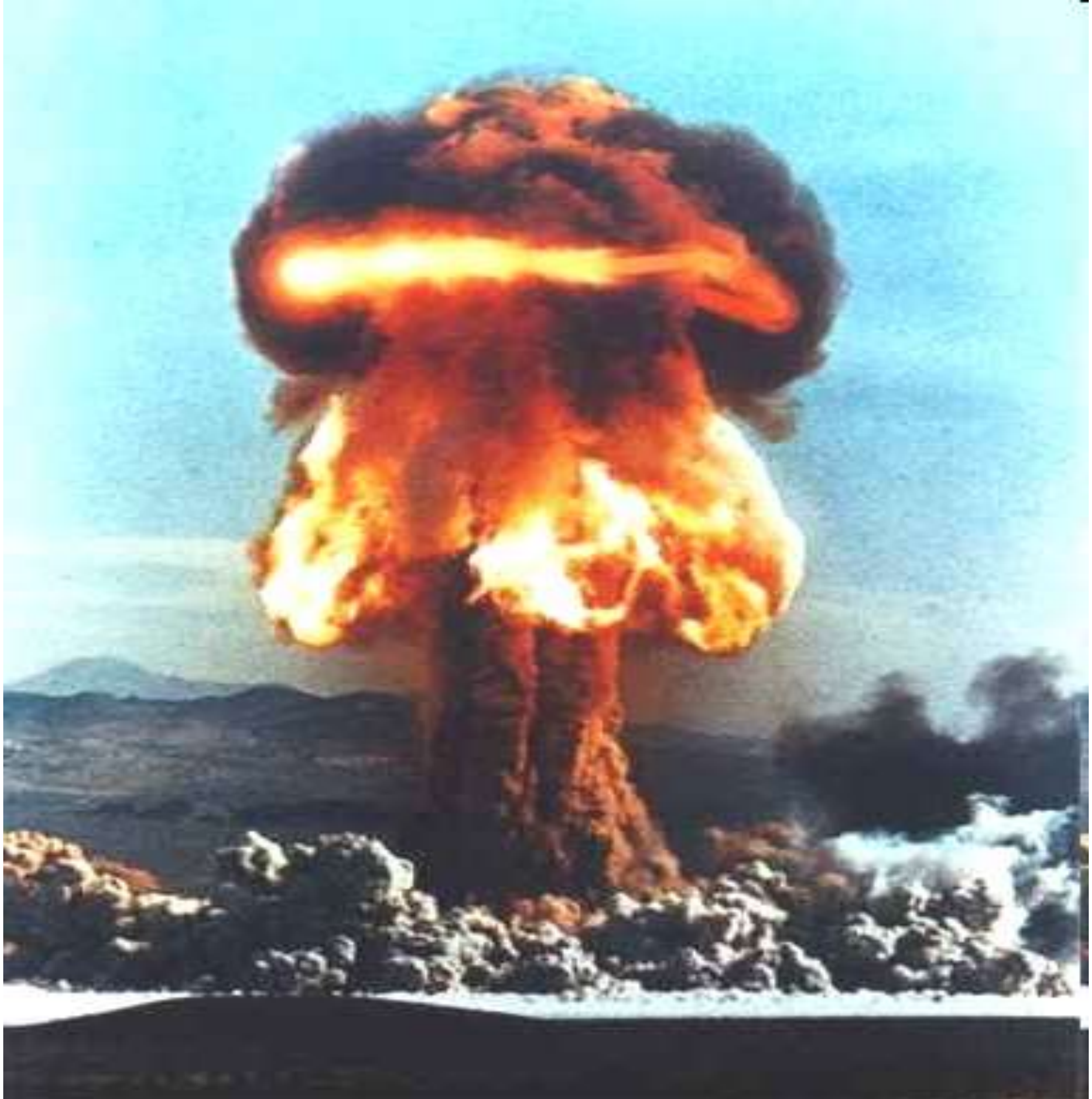
Also *fast neutrons* cannot carry out fission and are slowed by using a moderator (heavy water and graphite).



- **Why Uranium and Plutonium?**
- **U 238, is not suitable** for a nuclear weapon. There is a fairly high probability that an incident neutron would be captured to form uranium 239 instead of causing a fission. U 235 has a high fission probability.
- Of natural uranium, only 0.7% is uranium 235. ie . large amount of uranium is needed to obtain reqd quantities of uranium 235. Also, uranium 235 cannot be separated chemically from uranium 238, since the isotopes are chemically similar.
- Plutonium 239 would have a high fission probability but it is s not a naturally occurring element and would have to be made.

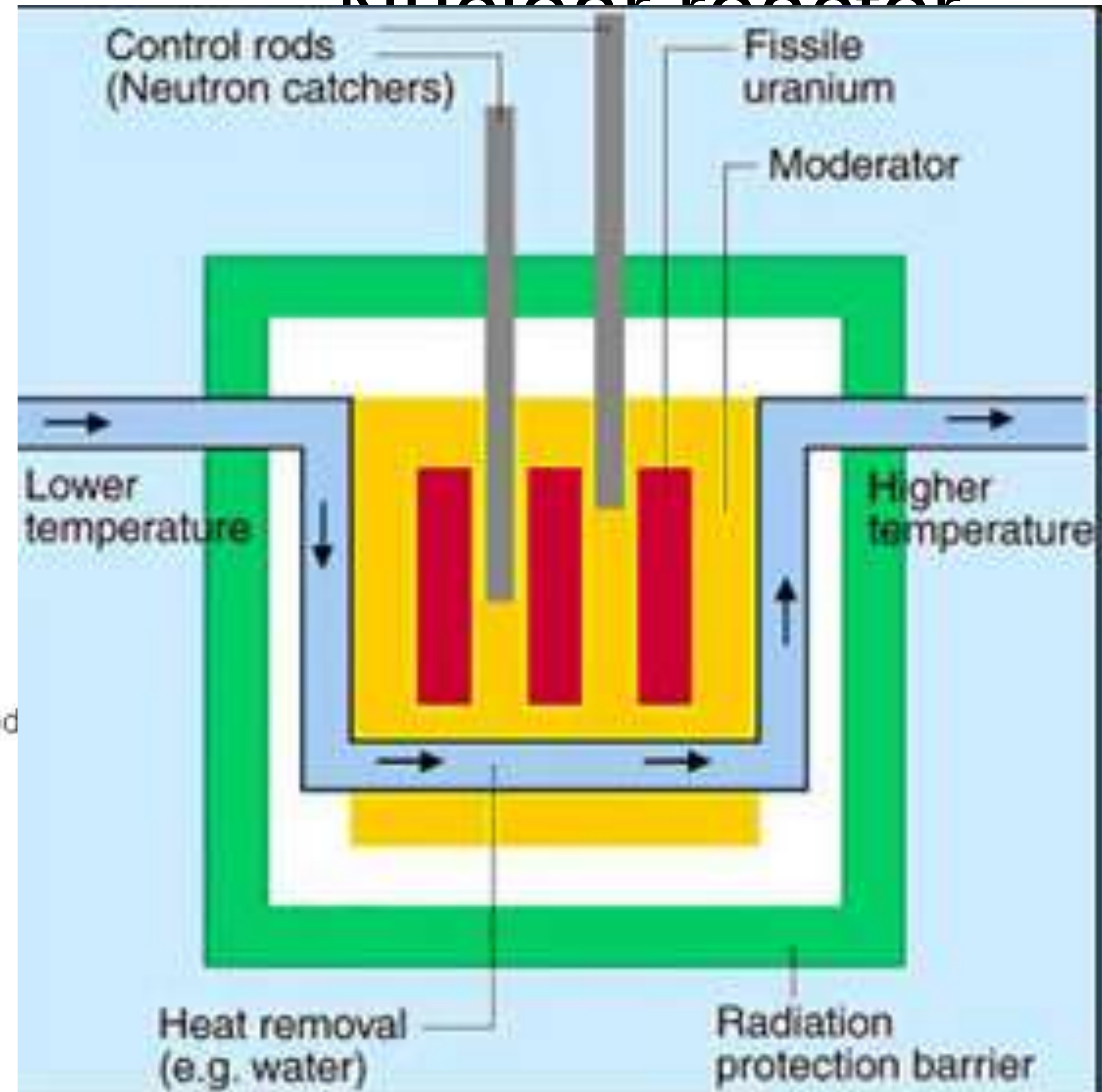
Working Principle of Atom Bomb – uncontrolled chain reaction

- Two or more pieces, each smaller than the critical size are kept separated by a small distance by a separator aperture. The surface area of each unit is relatively large and hence neutrons readily escape and no chain reaction takes place when they are kept apart. An explosive like TNT is suddenly dentonated behind the separated sub critical pieces and they are brought together. If there are only two sub critical masses in the form of hemisphere then a third small piece is introduced by the explosion. Now all the pieces are together and are greater than the critical mass.



Nuclear reactor

- A ... vice ir re c ... at a s
- T Mod ... of n e generation of electrical power



Essential parts of a nuclear reactor

i. Fuel

ii. Moderator

iii. Controlling material

iv. Coolant

v. Shield.

Fuel

$_{92}U^{235}$ is commonly used fuel.(Tarapur)

If its relative abundance is more than 0.72%, sample is called enriched Uranium.

Kalpakkom uses natural uranium as fuel.

Moderator

Fast neutrons released in fission should be slow down to cause further fission.

Moderators does it, (absorb energy from neutrons , will not absorb neutrons.)

Eg. D_2O and graphite. (ordinary water may also be used , but it generally absorb neutrons.)

Controlling materials

To absorb neutrons.

Eg. Cd, B (have good n absorption capacity)

Made in the form of rods and inserted into the fuel assembly to control chain reaction.

Coolant

Energy released should transferred from the reactor for useful purpose.

Coolant does it.

Eg. Air , CO_2, He, Water , liquid metal

Choice of coolant depends on the purpose of the reactor. (liquid sodium is effective for heat transfer)

shield

Thick shield blocks radioactive and high energy fission products from leaking.

Concrete is used.

Disadvantages of Nuclear Fission

Large radioactive waste is produced and disposal of radioactive waste is a complicated problem.

Nuclear Fusion

- Process by which two or more light nuclei fuse to form a heavy nucleus with the release of some amount of energy (called thermonuclear energy)
- Basic source of energy in stars and hence nearly all the energy in the universe.

At high temperature , light nuclei possess enough energy to overcome the force of electrostatic repulsion.

Only fission can produce such a high temperature and initiate fusion .

Mass difference into energy .

Fusion of deutron to helium average energy released is 24MeV.(this is much less compared to energy released / fission 200MeV).

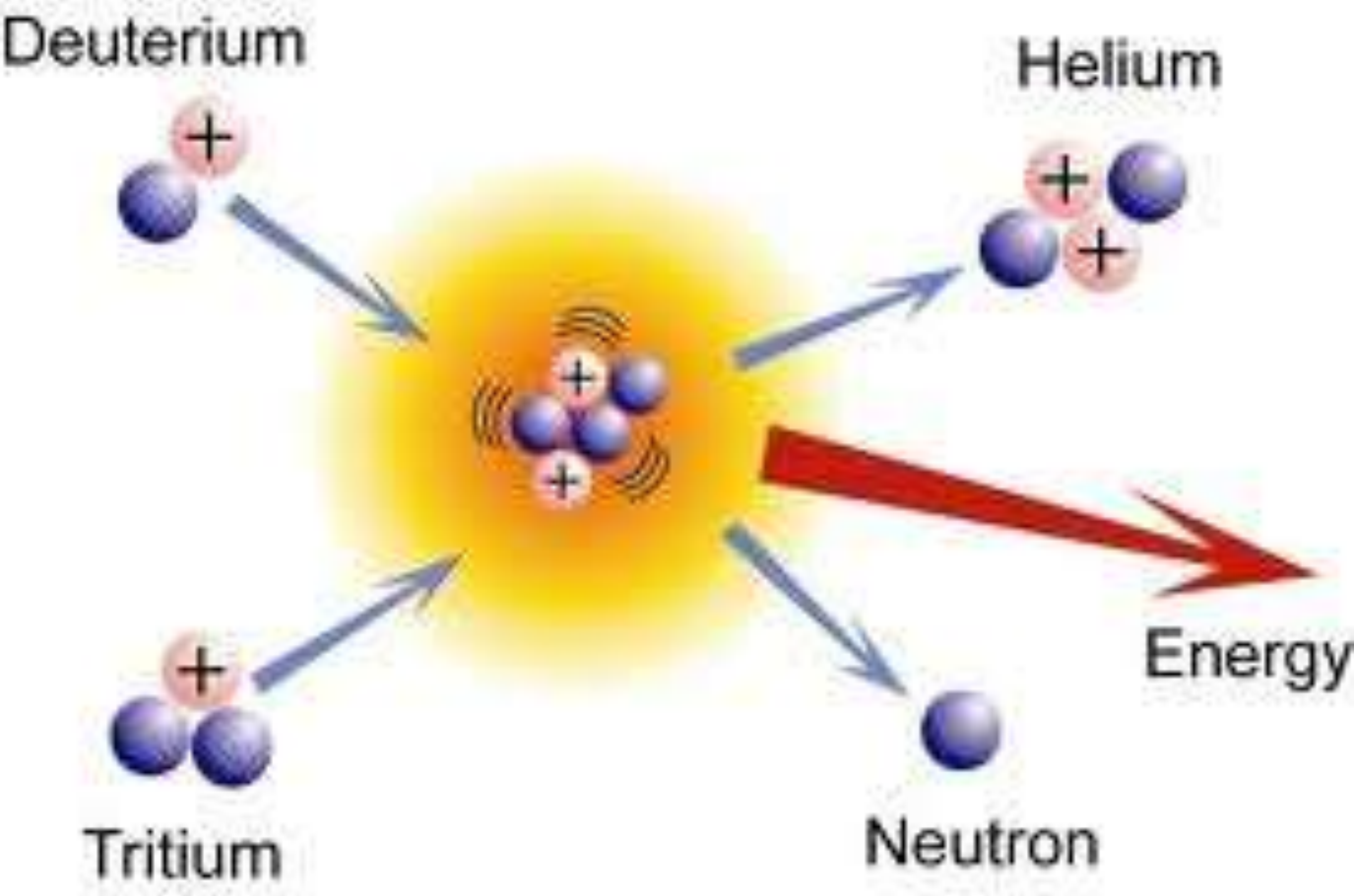
But lighter nuclei has larger no. of nuclei per unit mass, and hence average energy released / gm is very large.

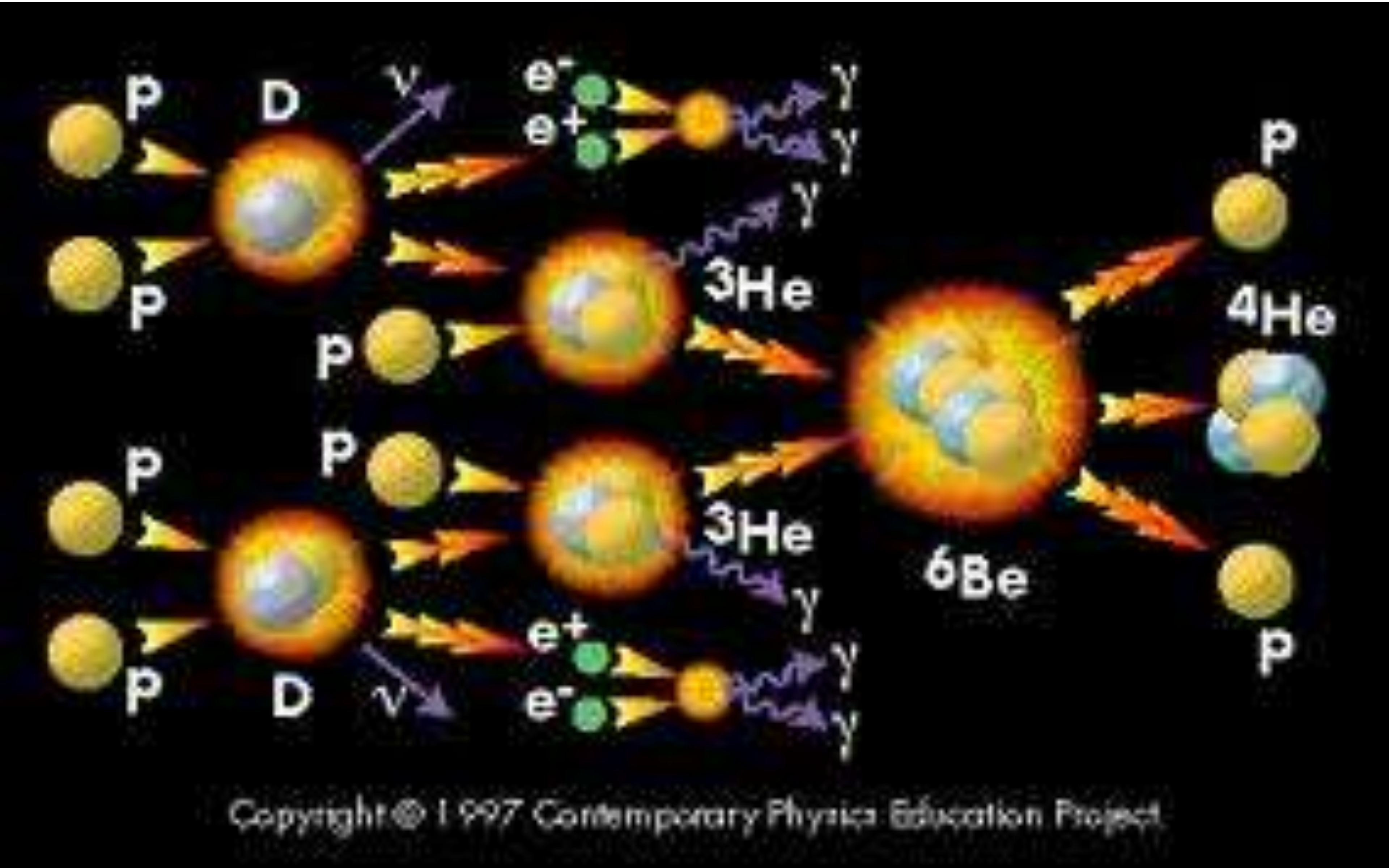
Needs high temp to initiate (10^7K – plasma state)

No controlled fusion so far.

Construction of a fusion reactor is very difficult.

Russian design called Tokamak is a major step to materialse this goal.


Deuterium
Helium
Energy
Tritium
Neutron


P
D
ν
e-
e+
γ
γ
γ
P
P
3He
P
4He
P
6Be
P
P
3He
γ
P
D
ν
e+
e-
γ
γ
P
Copyright © 1997 Contemporary Physics Education Project

Hydrogen bomb

Principle : uncontrolled fusion of hydrogen nuclei.

First tested by USA in 1952.

In H bomb , fusion of 3Li6 and 1H2 gives two helium .

Advantages of fusion bomb over fission bomb

i. There is no upper limit for energy .
ii. There no critical size for fusion bomb.
iii. Will not explode without igniting.

Sources of energy in sun and stars

Source – fusion .

Stars are formed by dust and gases due to gravitational pull.

Pressure and temperature increases to a very high value sufficient for fusion .

Light nuclei fuses to form heavy nuclei and star radiates or shines.

Types of fusion in stars

i. p-p cycle : $_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + e^+ + \nu$

$$_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma$$

$$_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + 2\,{}_1H^1 + Q$$

$$Q \approx 24.7 \text{ MeV}$$

Seen when internal temperature is less than 1.6×10^7K (Small stars. Sun temp = 1.5×10^7K)

p-p cycle is generally slow- long life of sun.

Types of fusion in stars

ii. C-N cycle (CNO) $_{1}H^{1} + {}_{6}C^{12} \rightarrow {}_{7}N^{13}$

$_{7}N^{13} \rightarrow {}_{6}C^{13} + e^{+} + \nu$

$_{1}H^{1} + {}_{6}C^{13} \rightarrow {}_{7}N^{14} + \gamma$

$_{1}H^{1} + {}_{7}N^{14} \rightarrow {}_{8}O^{15} + e^{+} + \gamma$

$_{8}O^{15} \rightarrow {}_{7}N^{15} + e^{+} + \nu$

$_{1}H^{1} + {}_{7}N^{15} \rightarrow {}_{6}C^{12} + {}_{2}He^{4} + Q$

Energy released is 24.7MeV.

Initial $_{6}C^{12}$ remains as such after one complete cycle of reaction and act as a catalyst. (seen in massive stars whose temperature is greater than 1.6 x 10^{7}K)

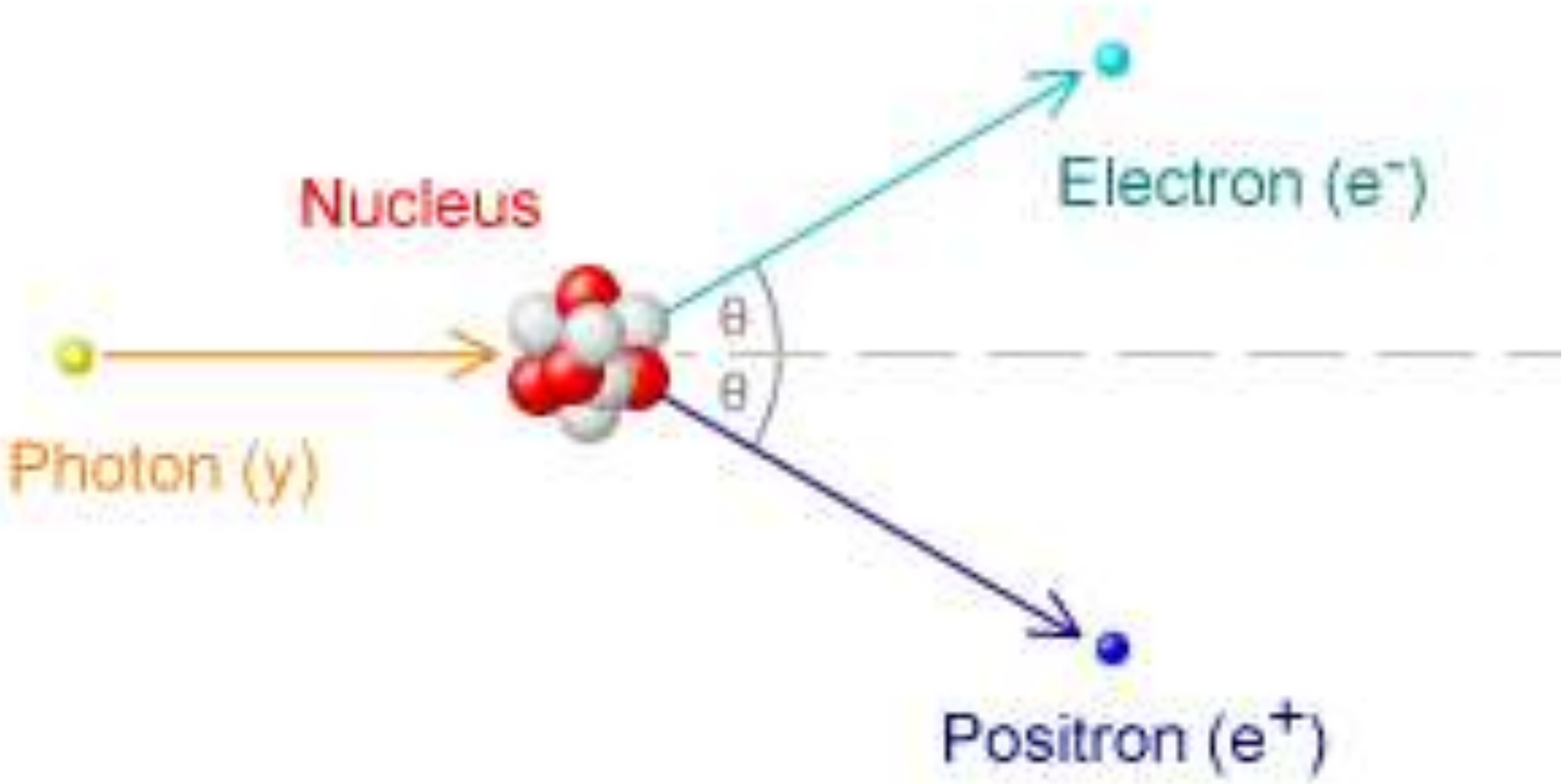
Pair production - creation of an elementary particle and its antiparticle (usually from a photon)

occurs when a high-energy photon interacts in the vicinity of a nucleus

Energy of photon will be converted into mass through Einstein's famous equation $E=mc^2$

If energy of the photon is high enough to make mass (=2me) then an electron-positron pair may be created

Pair production



Pair annihilation : occurs when an electron and a positron collide results in the creation of gamma ray photon

$$e^- + e^+ \rightarrow \gamma + \gamma$$