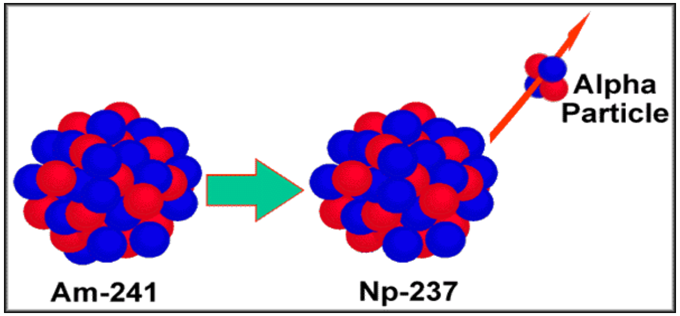
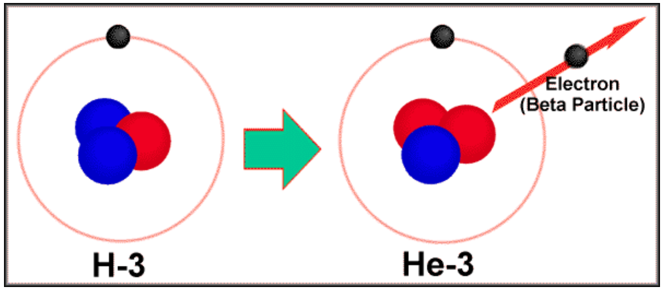
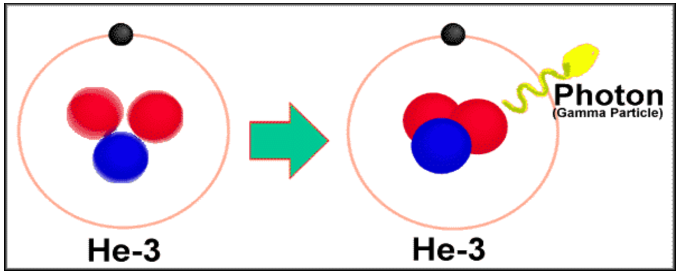
Half-Life with Dice

Radioactive decays: Every unhappy nucleus is unhappy in its own way

- Alpha Decay: An unstable nucleus spits off an alpha particle (He nucleus). Light nuclei can't do this.
- Beta – Decay: A neutron inside nucleus changes to a proton, giving off an electron (aka beta particle) and neutrino.
- Beta + Decay: A proton inside nucleus changes to a neutron, giving off a positron (aka beta + particle) and neutrino.
- Electron Capture: A proton inside a nucleus captures an orbiting electron, changing it to a neutron. A neutrino is emitted.
- Gamma Decay: A photon is emitted (like visible light only much more energetic).







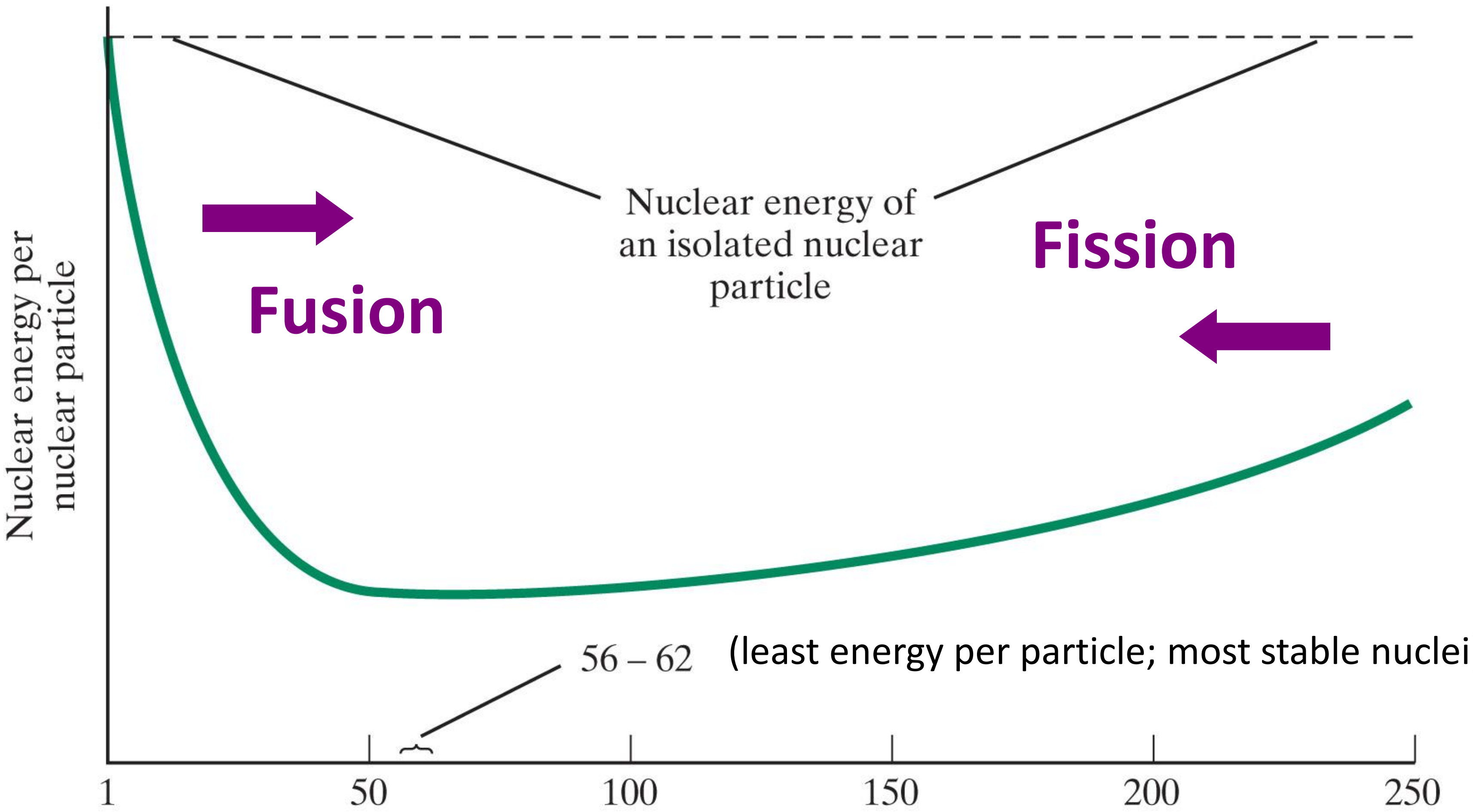
Nuclear Fusion and Fission

- Fission:
  - ➢Nuclear power reactors.
  - ➢Nuclear warheads.

- Fusion:
  - ➢Energy of the stars.
  - ➢"Thermonuclear" weapons.

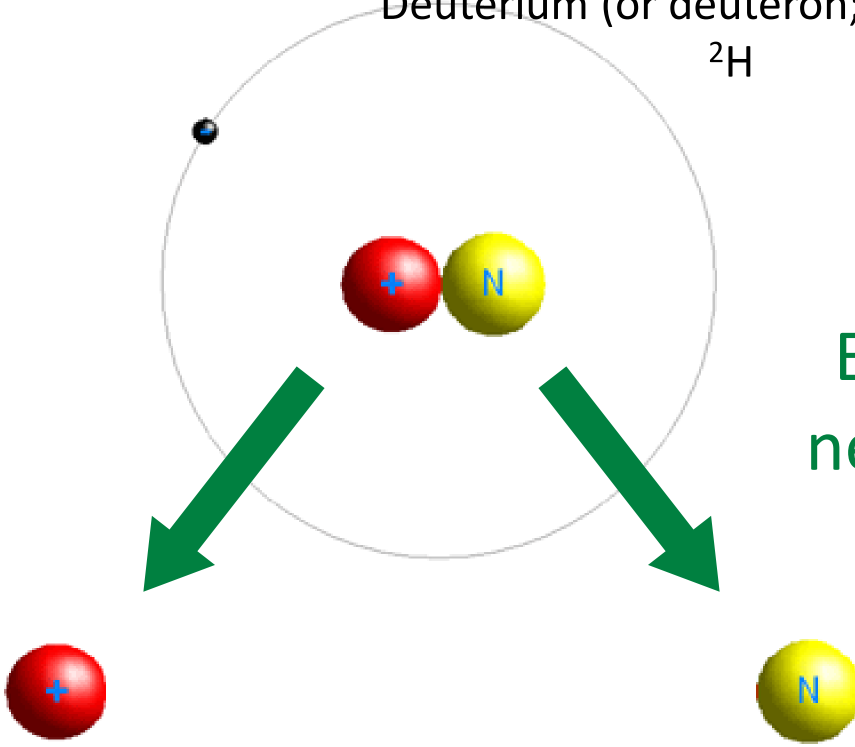
Plot: rest mass/rest energy per particle for all nuclei (not to scale).

- Iron (mass number 56) is the most stable element.
- Lighter nuclei can give off energy when they fuse.
- Heavier nuclei can give off energy if they spit (fission).



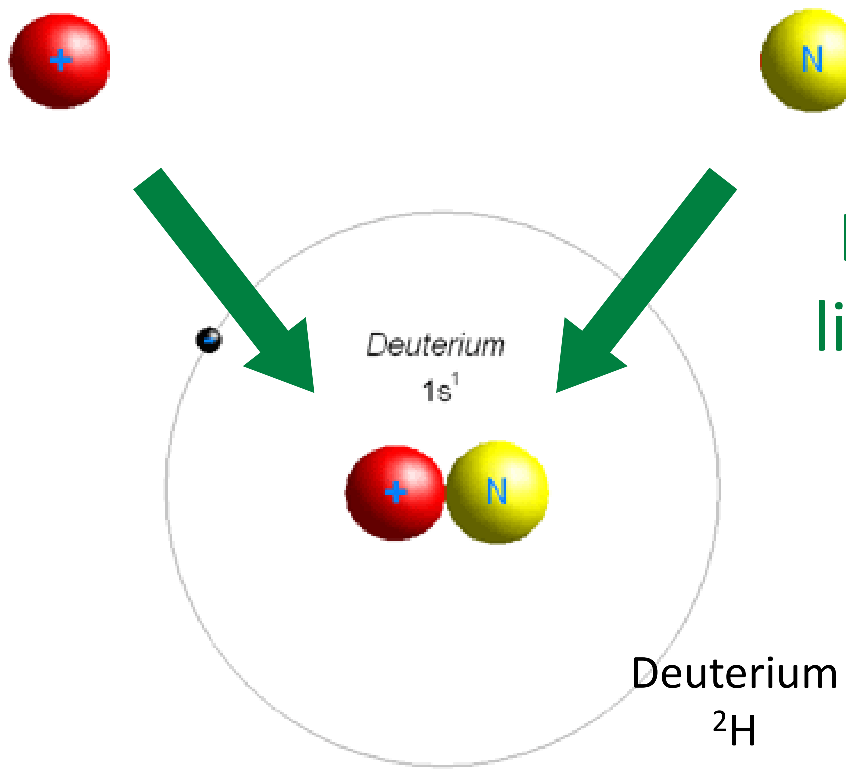
Deuterium (or deuteron; 1p and 1n)

^{2}H



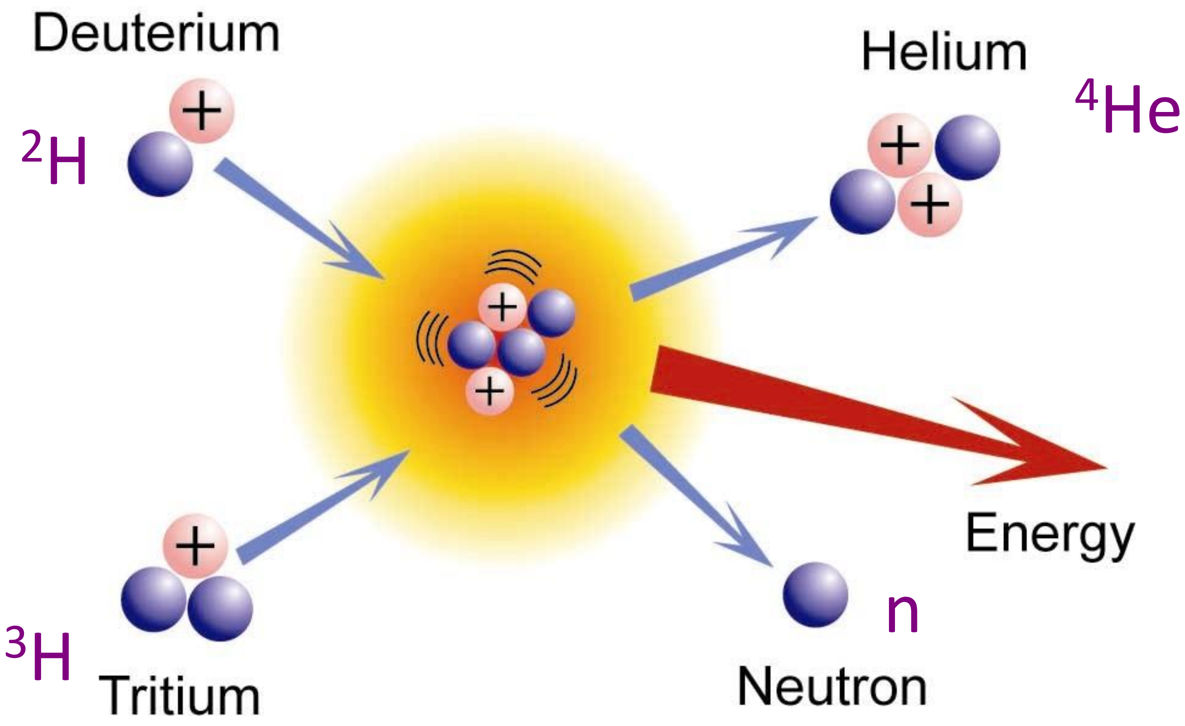
Enormous energy needed to separate them

Nuclear Fusion



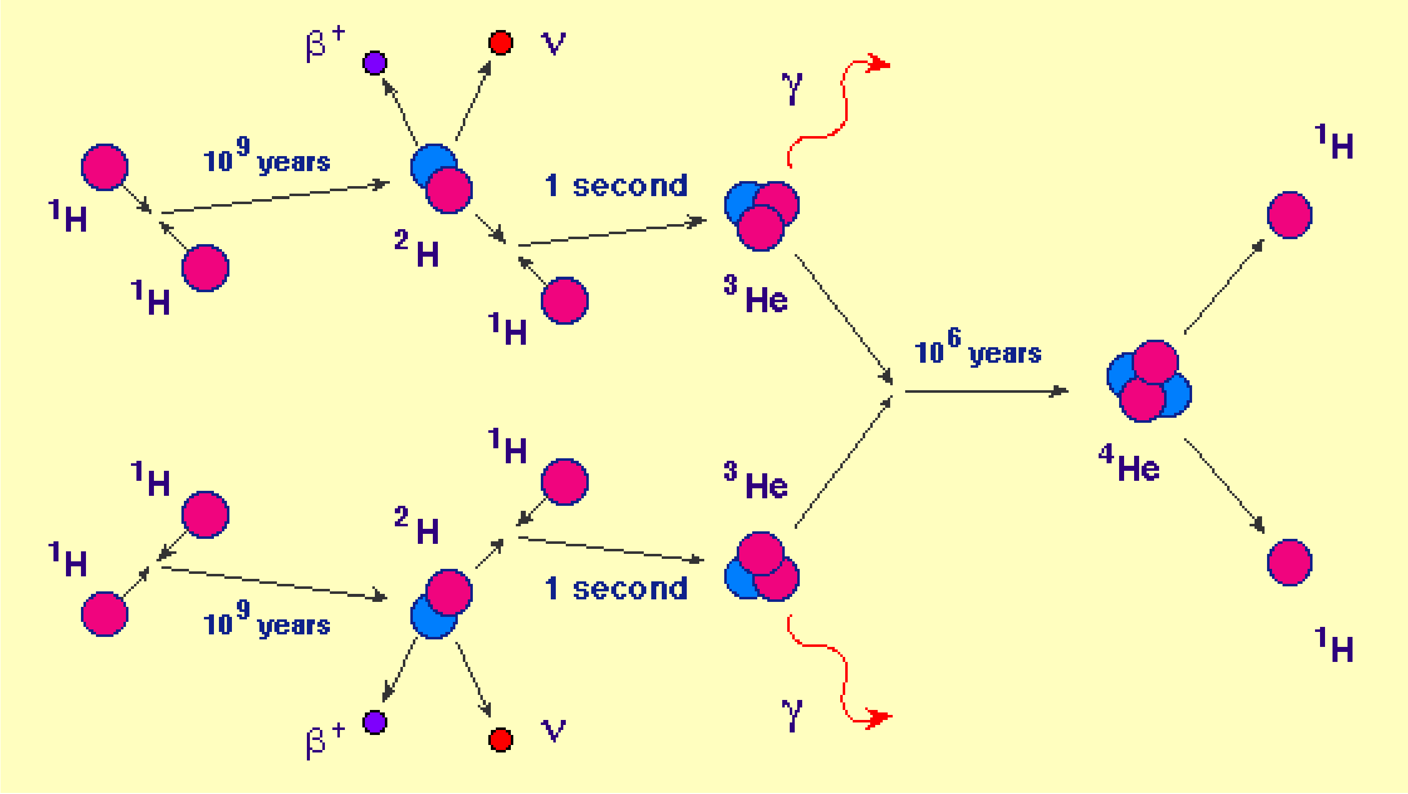
Enormous energy liberated by joining them

Fusion Reaction

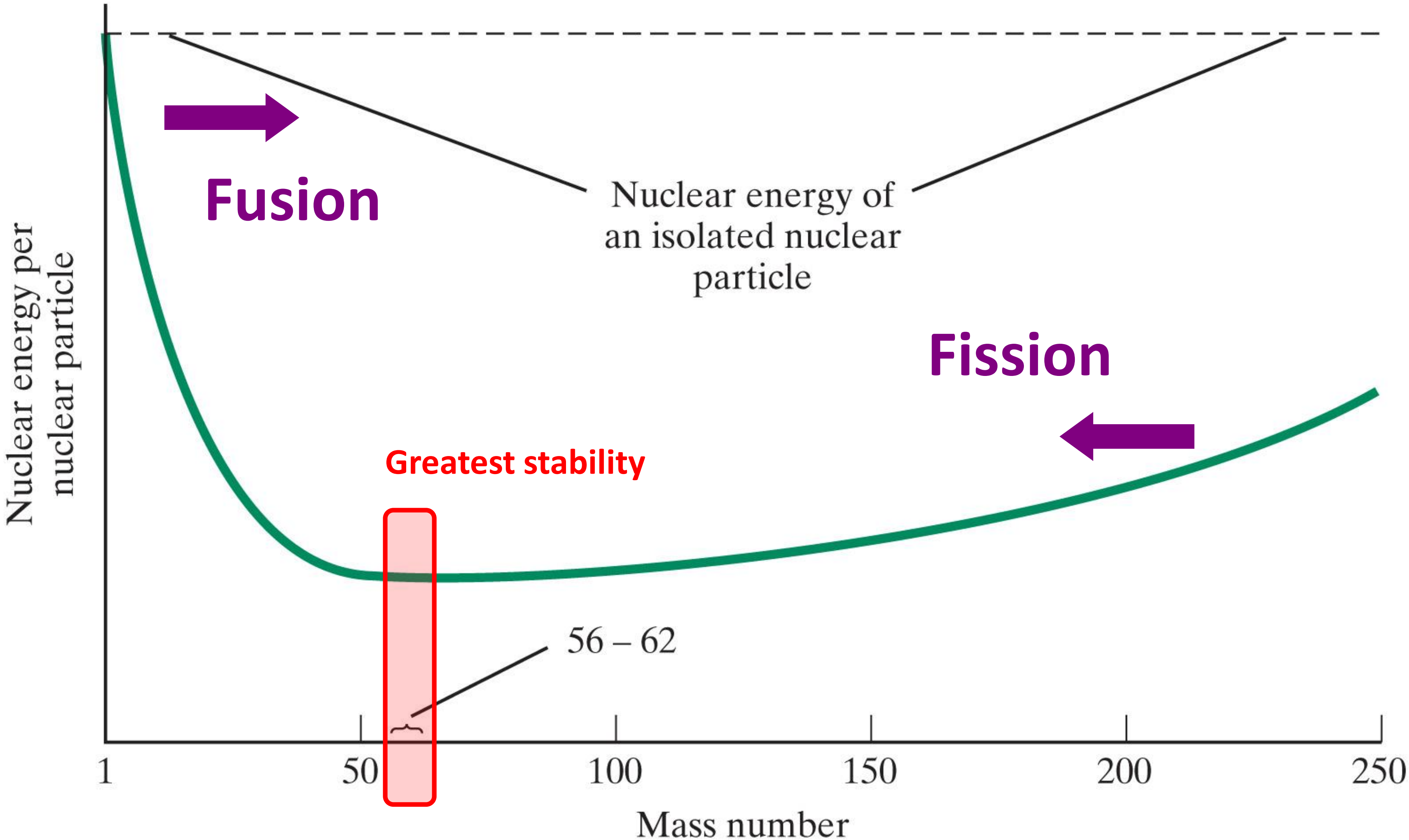


Because the positively charged hydrogen nuclei repel each other, this happens only at very high temperatures.
Fusion requires temperatures of about 100 million Kelvin!

Fusion in Stars: Proton-Proton Chain



Hydrogen $\Rightarrow$ Helium + energy released


Nuclear energy per nuclear particle
Nuclear energy of an isolated nuclear particle
Fusion
Fission
Greatest stability
56 – 62
1
50
100
150
200
250
Mass number

The Periodic Table of the Elements

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

Fusion

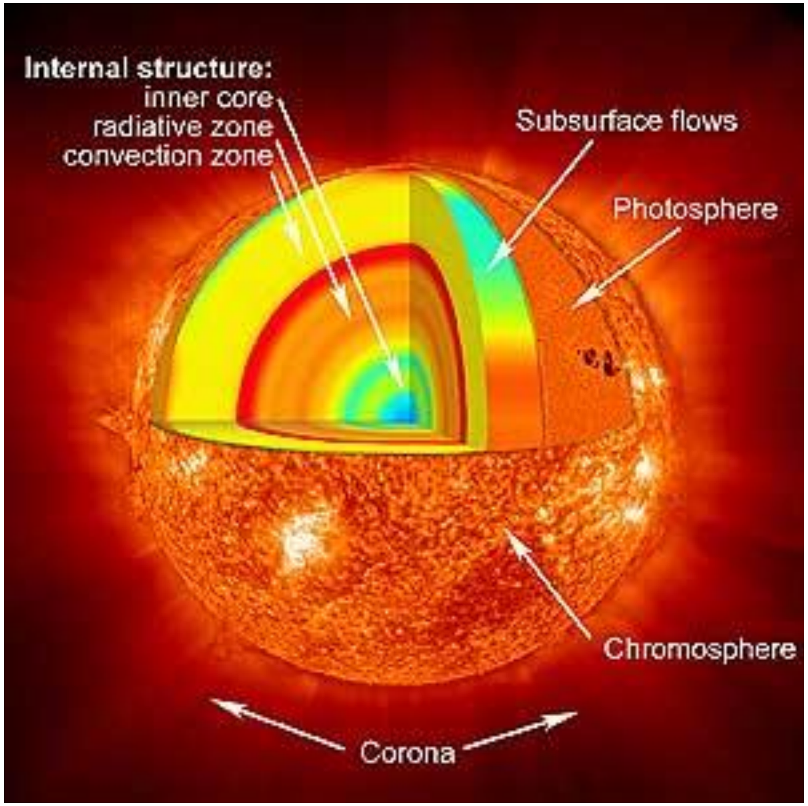
Greatest stability

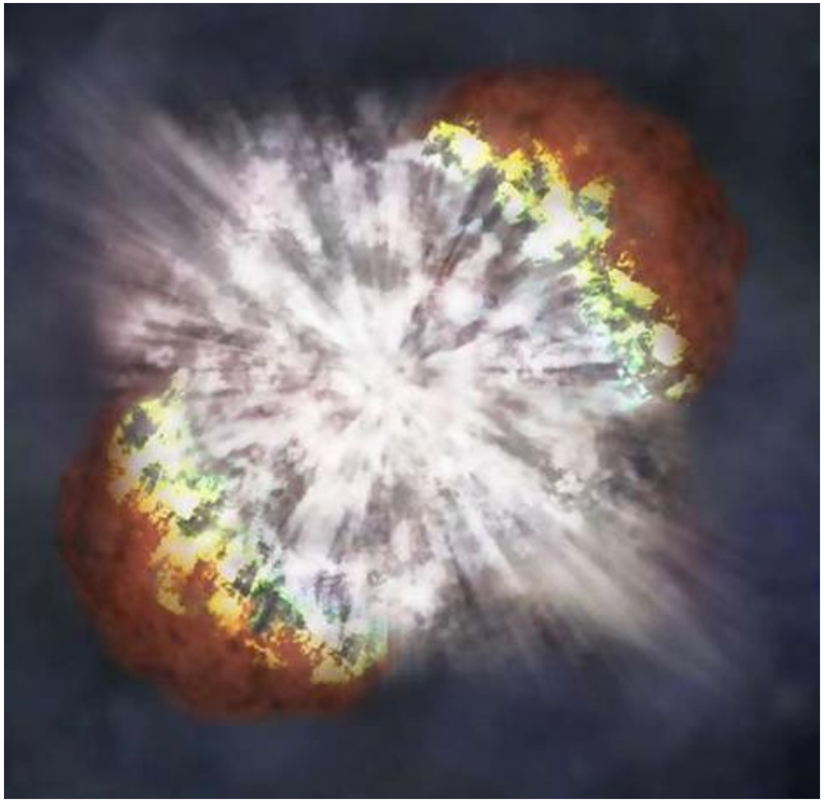
Fission

How were lighter elements made?

How were heavier elements made?

Origin of Elements





Light elements:

- Made by fusion in **stars**
- Dispersed by **supernovas**

Heavy elements:

- Made by fusion during **supernovas**
- Dispersed during **supernovas**

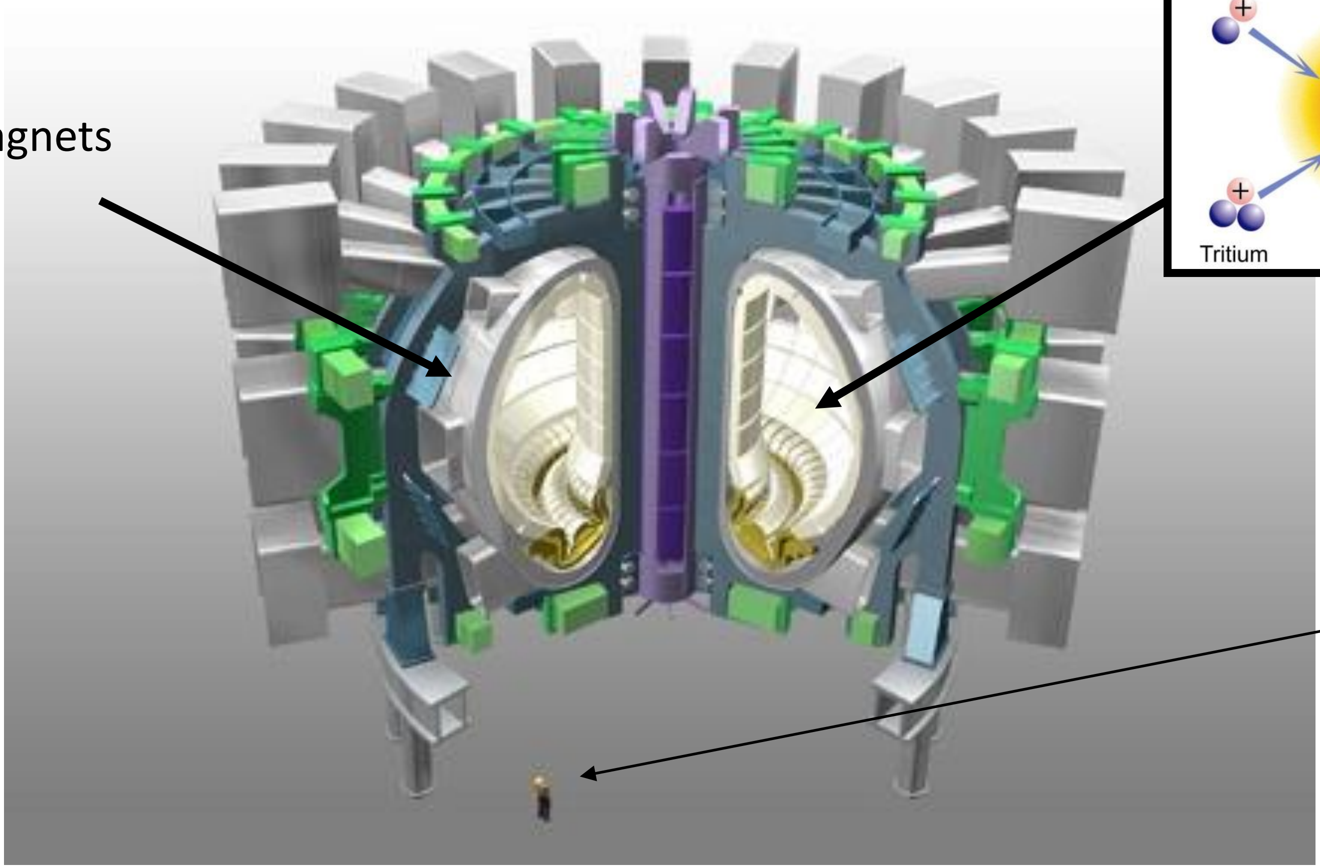
Vocabulary Lesson

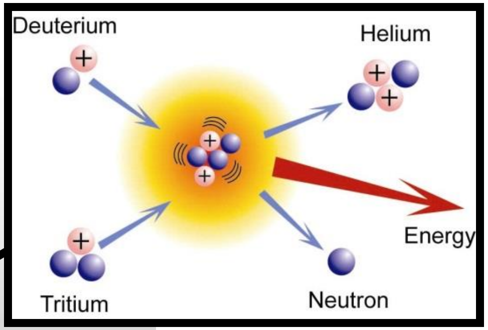
- "*Nuclear*", not "*nucular*". *(sigh…)*
- "*Nuclear*" reactions, weapons can be either fission or fusion.
- Strangely, "*atomic*" is used as a synonym for "*nuclear*".
- "*Thermonuclear*" refers to fusion.
- "*H-bomb*" refers to fusion.
- "*Atom bomb*" usually means fission.

Peaceful uses of fusion?

ITER reactor under construction in France

Toroid magnets

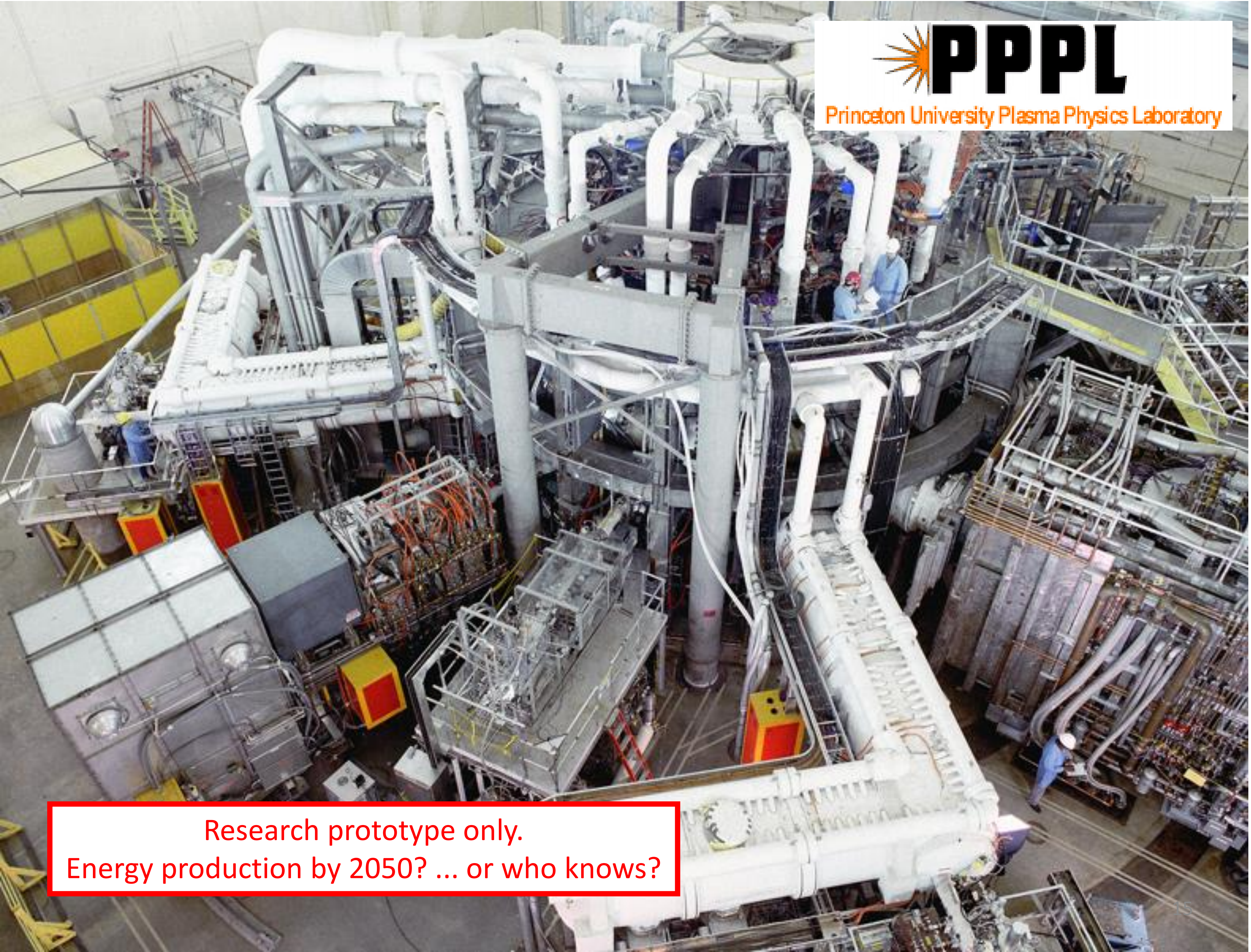




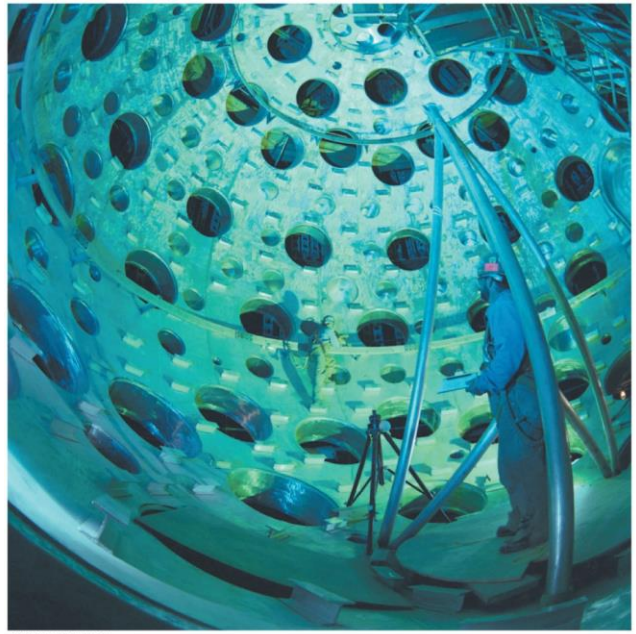
Person

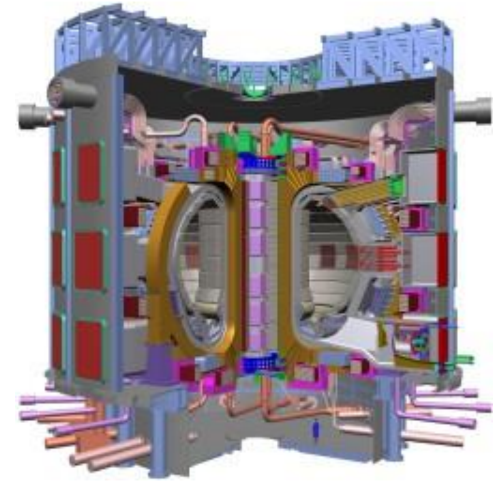
Challenges:

- Heat Fuel to 100 million degrees
- Keep it from touching container walls
- Use "magnetic confinement"


PPPL
Princeton University Plasma Physics Laboratory
Research prototype only.
Energy production by 2050? ... or who knows?

Fusion Energy Production Schemes





The Sun + Photovoltaics:

This is available and competitive **today**!

Inertial confinement: Livermore National Ignition Facility: 192 lasers with 5×10^{14} W implode small H pellets.

Magnetic confinement:

Tokamaks

Stellerators

Magnetic mirrors

Moving target: Energy production is perpetually promised to be about 20-30 years away ☹. Don't hold your breath.

Clicker

Hydrogen must be raised to a high temperature before it will undergo fusion because

A) This reaction consumes more thermal energy than it produces.

B) High temperatures are needed to overcome the “strong nuclear force” between H nuclei.

C) High temperatures are needed to overcome the electric repulsion between H nuclei.

D) Fusion and all other forms of chemical combustion must be initiated by high temperatures.

E) All nuclear reactions take place only at high temperature.

Clicker

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Clicker

Except for H, He, and a little Li, the lower-mass elements (lighter than iron) that are spread throughout the dust of the universe were created

A) right after the big bang.

B) during the shock of a supernova.

C) in hot white dwarf stars.

D) in quasars.

E) during the fusion process that powers the stars, then released during supernovas.

Clicker

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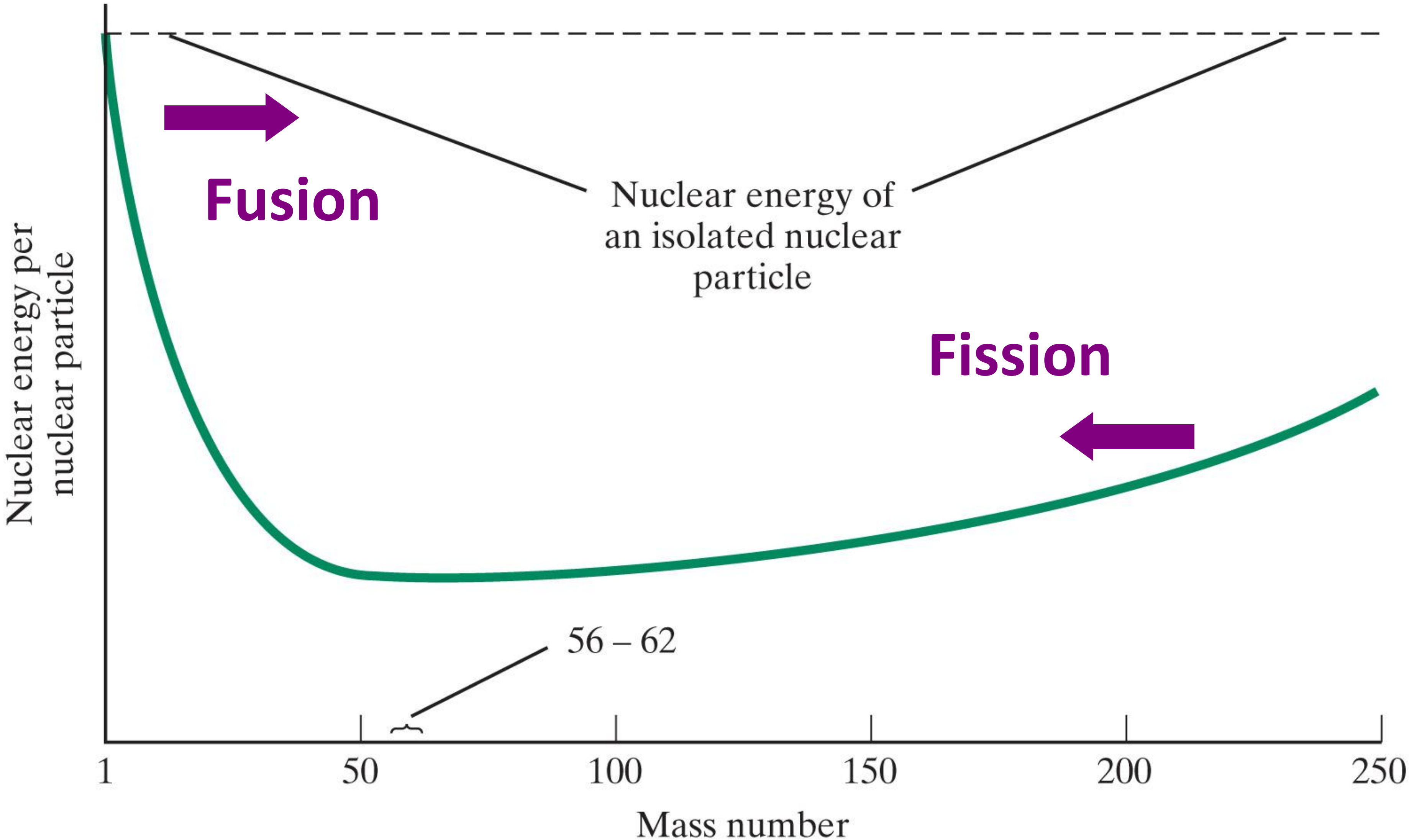
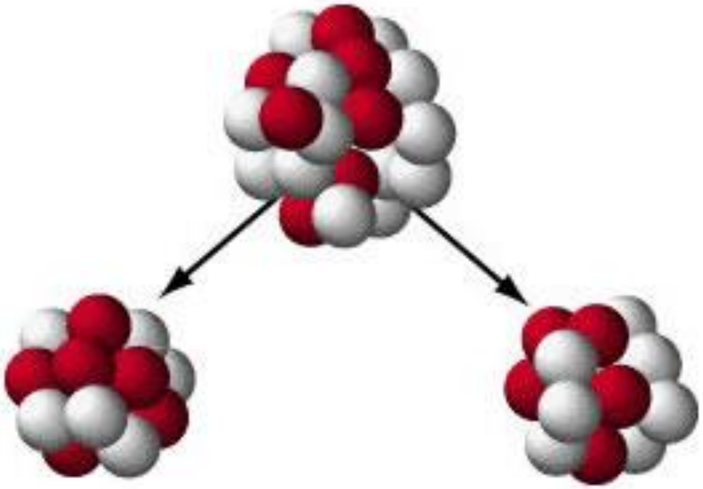

Fusion
Fission
Nuclear energy of
an isolated nuclear
particle
Nuclear energy per
nuclear particle
56 – 62
1
50
100
150
200
250
Mass number

What is Nuclear Fission?

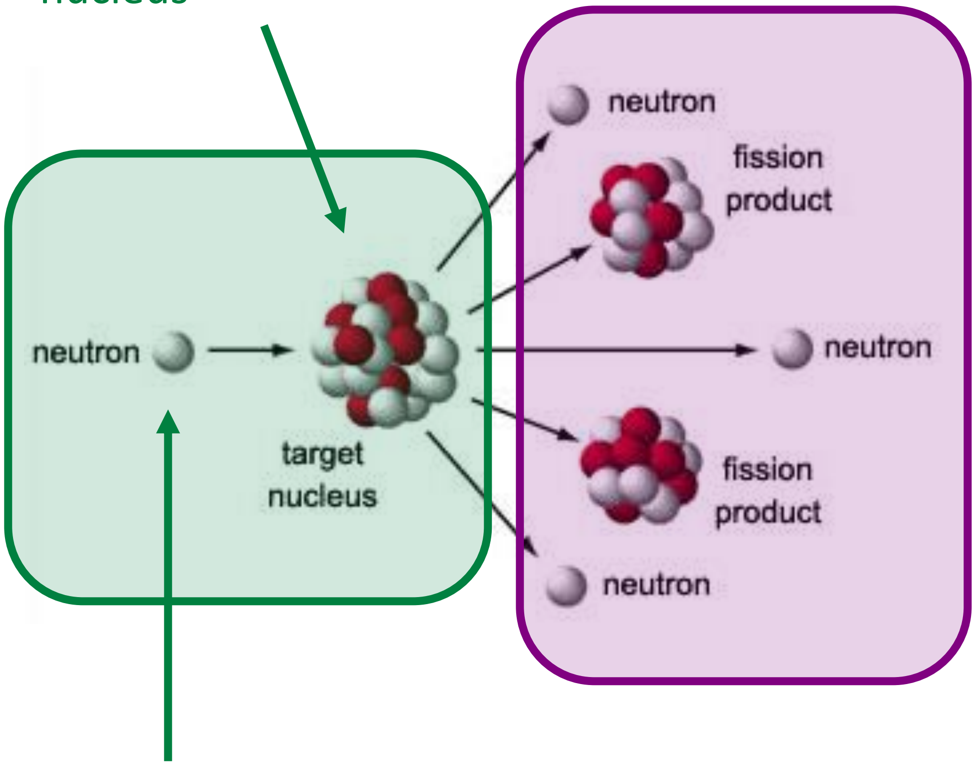


But it’s not that simple.
Doesn’t happen by itself!

Fission

Neutron strikes
heavy "parent"
nucleus

Reactants



Products:

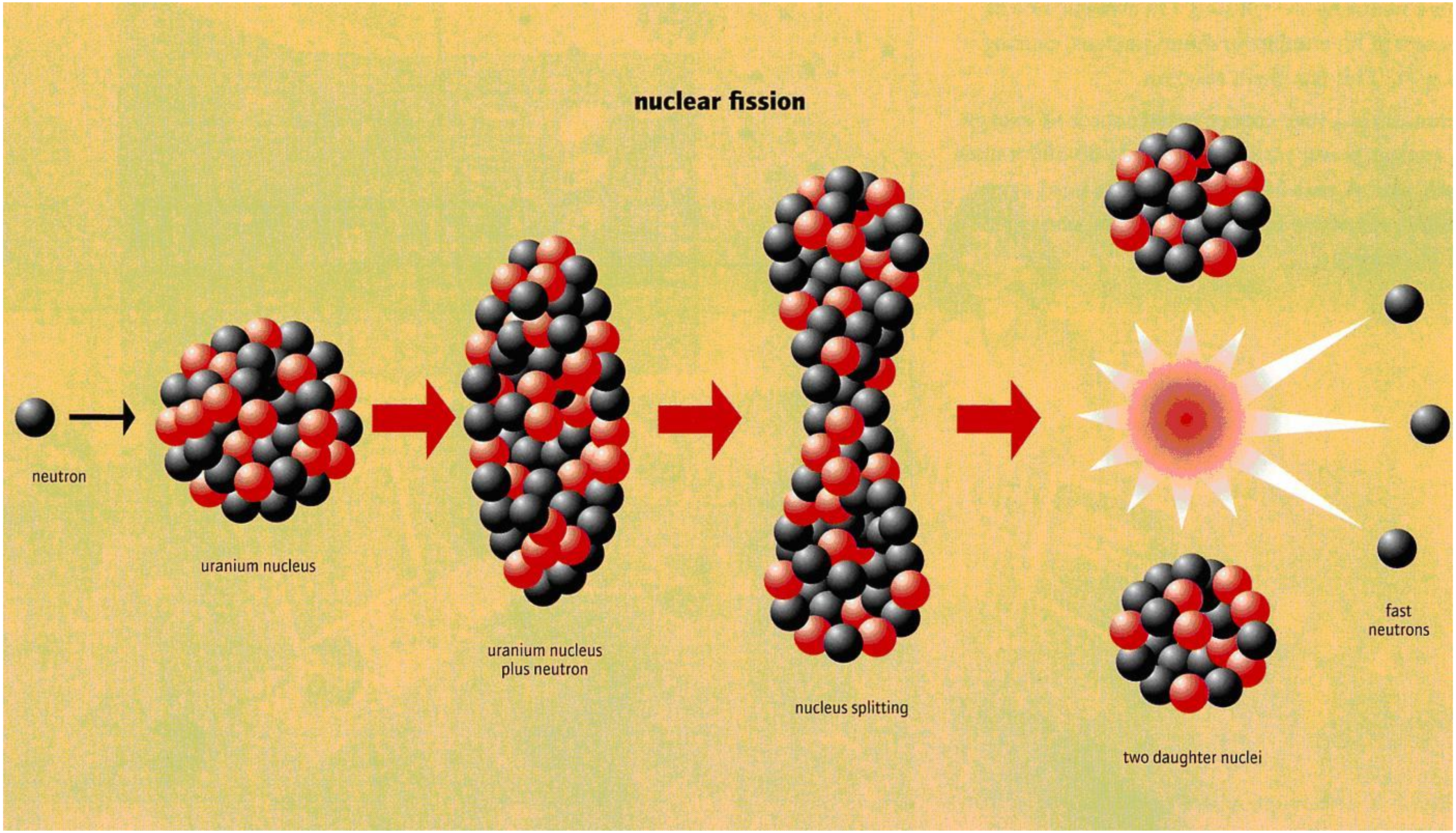
Two lighter "daugher nuclei"

+

3 neutrons

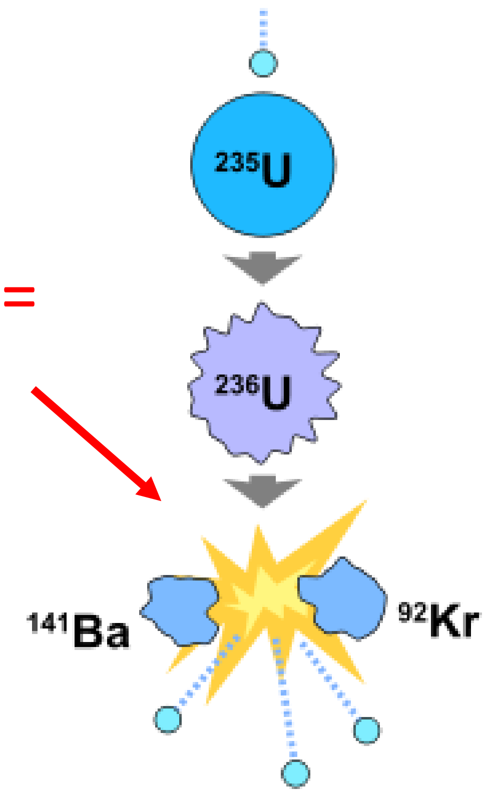
Need 1 neutron
to get it started

Fission


nuclear fission
neutron
uranium nucleus
uranium nucleus
plus neutron
nucleus splitting
two daughter nuclei
fast
neutrons

Fission: Example

Energy released = $(\Delta m_0)c^2$!



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

Energy Release

Let

$m_0(\text{reactants}) = m_0(^{235}\text{U}) + m_0(n)$

Let

$m_0(\text{products}) = m_0(^{141}\text{Ba}) + m_0(^{92}\text{Kr}) + 3m_0(n)$

Which is true?

A. $m_0(\text{reactants}) < m_0(\text{products})$?

B. $m_0(\text{reactants}) = m_0(\text{products})$?

C. $m_0(\text{reactants}) > m_0(\text{products})$?

Energy Release

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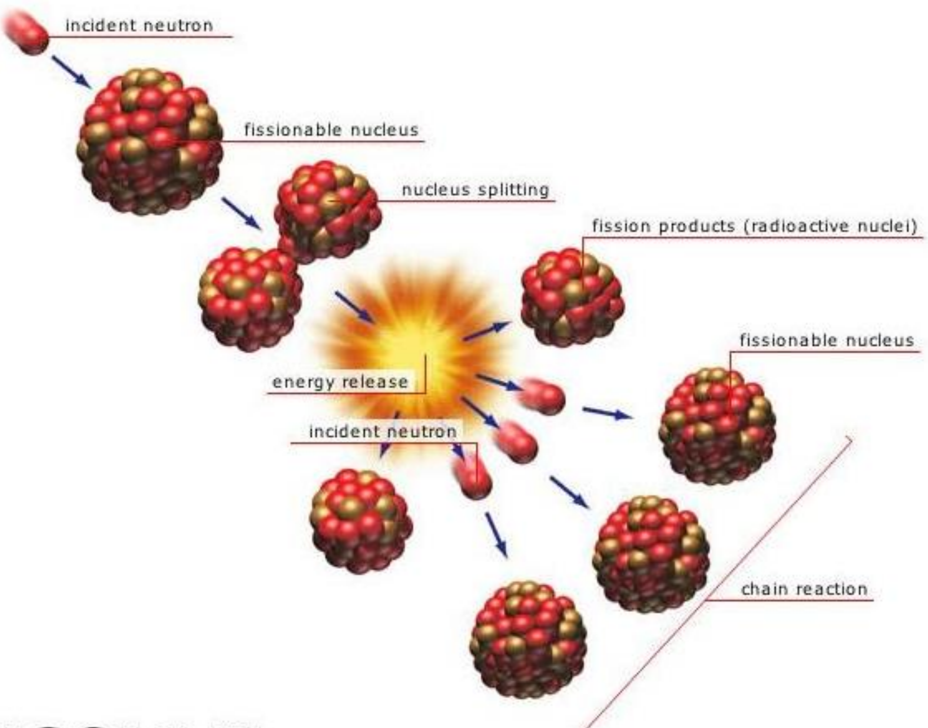
C. $m_0(\text{reactants}) > m_0(\text{products})$?

Energy released = $(\Delta m_0)c^2$!

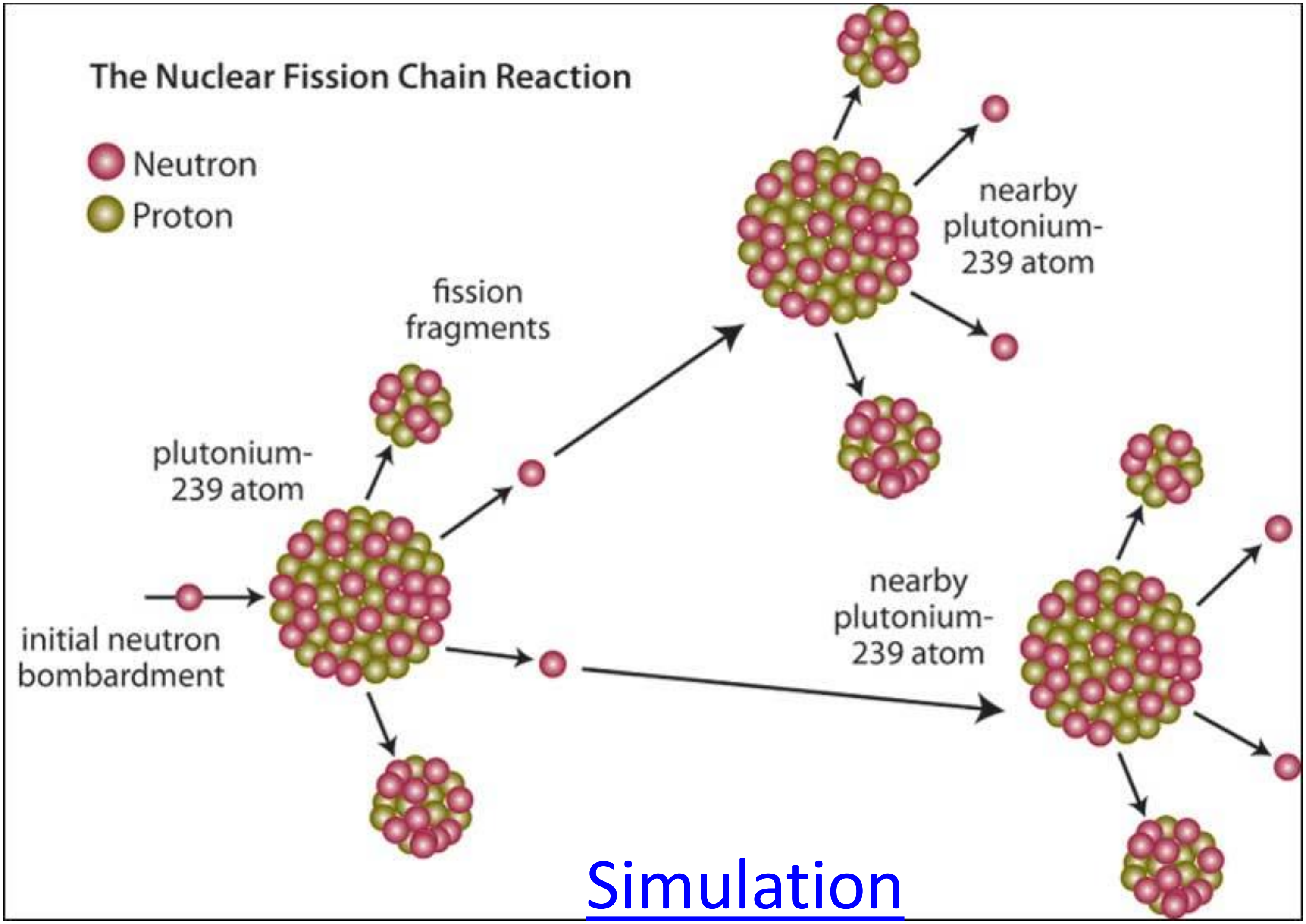
Fission

- Unlike fusion, fission process can happen at room temperature.
- But what do we need to get it going?
  - Neutrons ("slow" or "thermal" neutrons)
- Where do we get them?
  - Chain reaction …



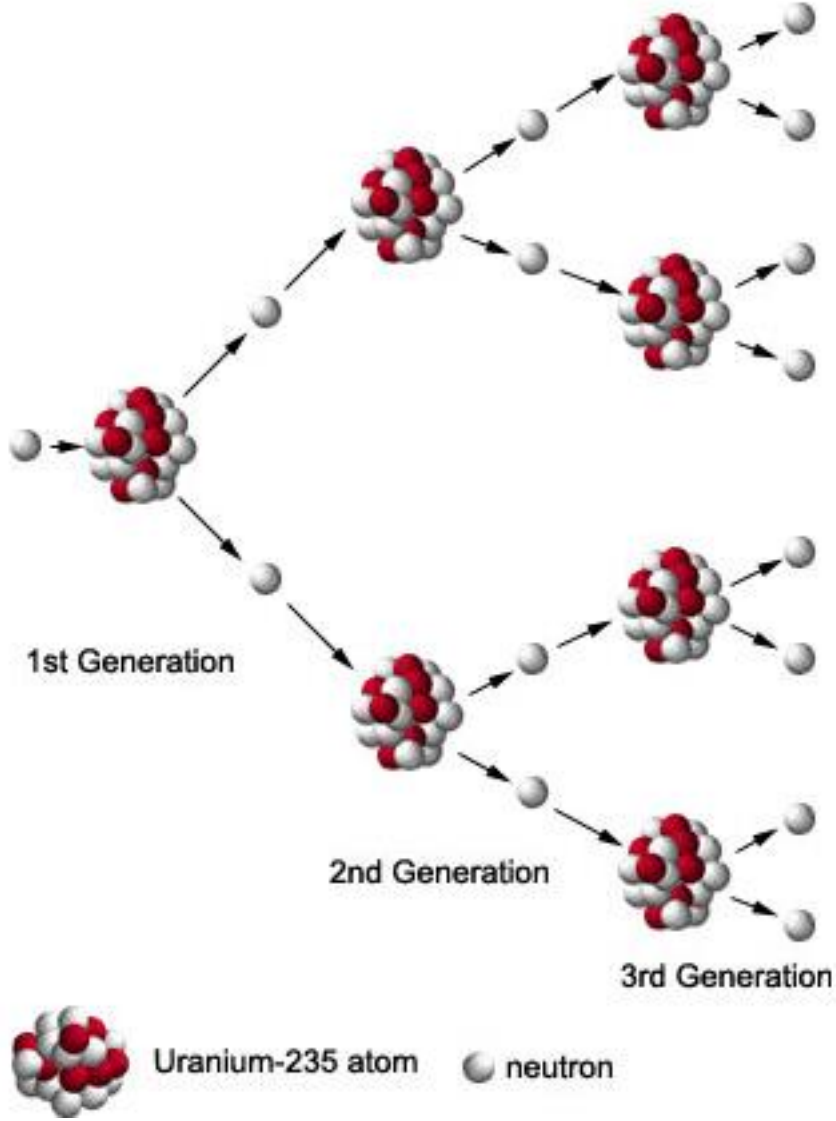
[Simulation]()

Chain Reaction



Simulation

Runaway Chain Reaction



Isotopes of Uranium

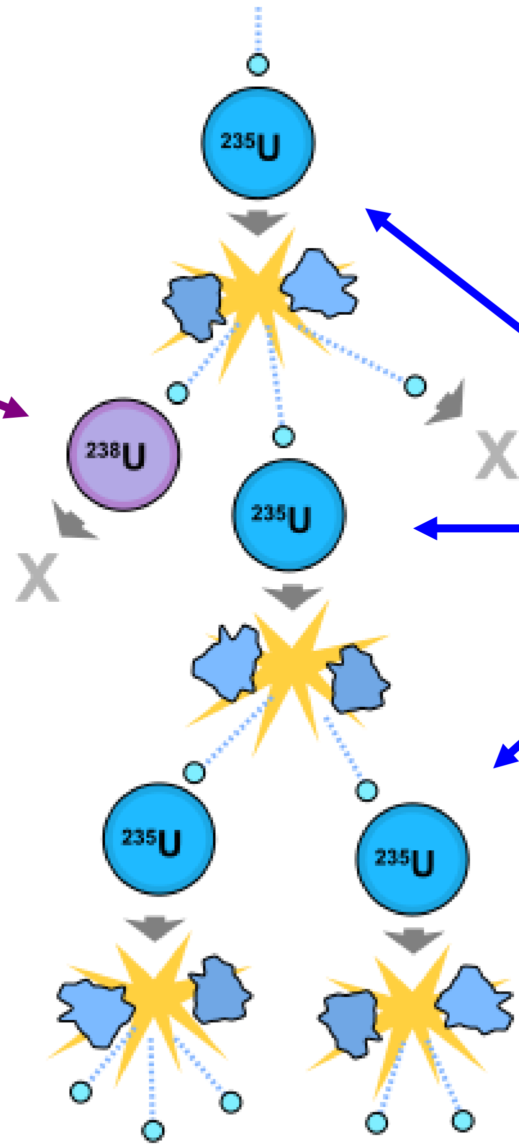
Uranium 238 (^{238}U)
- α decay lifetime of 5 billion years
- 99.3% abundance
- Not fissionable

Uranium 235 (^{235}U)
- α decay lifetime of 700 million years
- 0.7% abundance
- Fissionable!

Fission of Uranium

^{238}U is inactive

(But absorbs neutrons)



^{235}U is fissionable

Uranium Enrichment

- ^{238}U absorbs neutrons harmlessly
- In natural uranium, 0.7% abundance of ^{235}U is not enough to sustain a chain reaction
- Need larger fraction of ^{235}U for chain reaction

Simulation

Need 3-4%

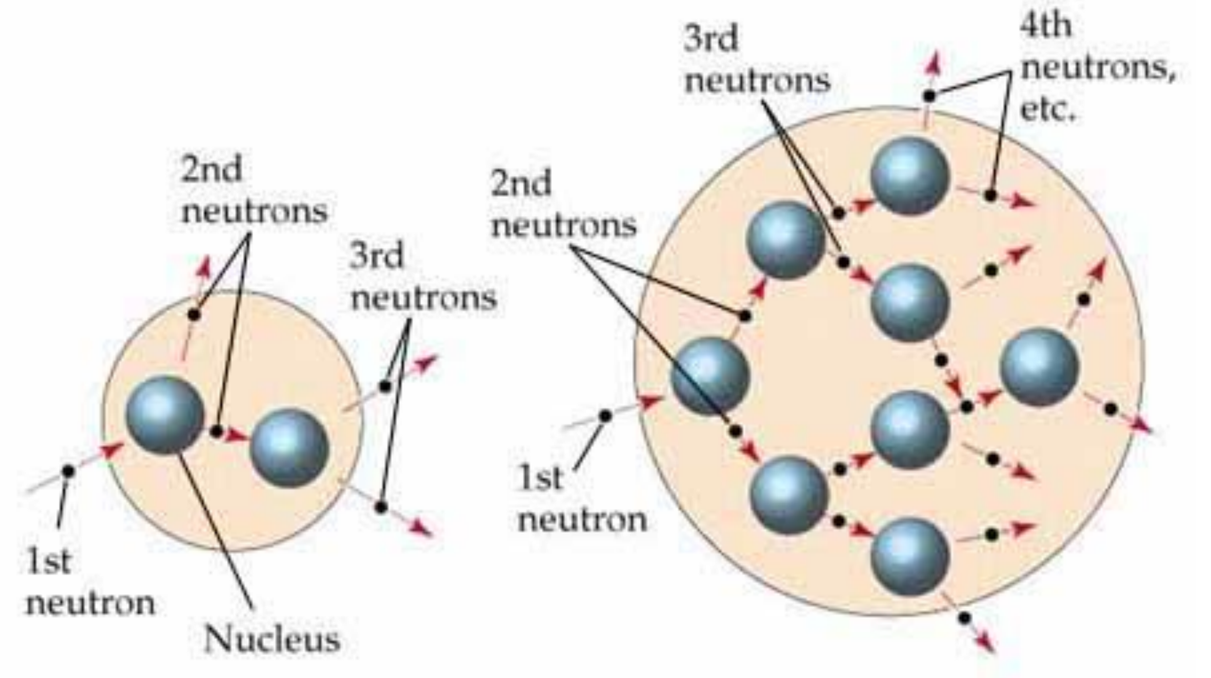
Need 90%

Critical Mass

A "critical mass" of fissile material is needed for a chain reaction.

- Subcritical: no chain reaction; too many neutrons absorbed/lost
- Supercritical: chain reaction accelerates; can lead to a nuclear explosion
- Critical: goal for nuclear reactors

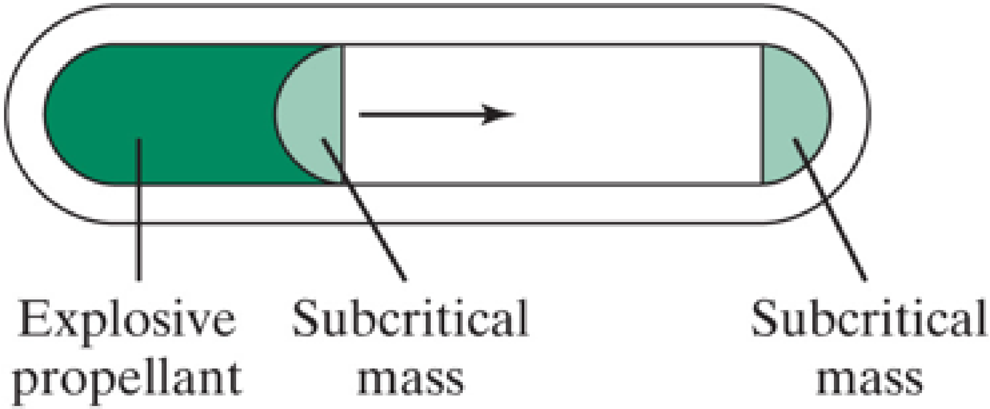
Simulation

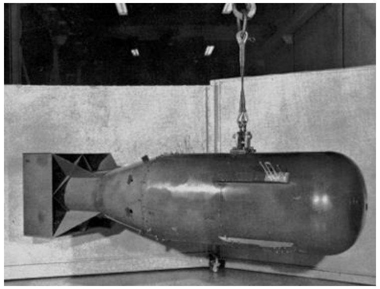


Subcritical mass
(chain reaction stops)

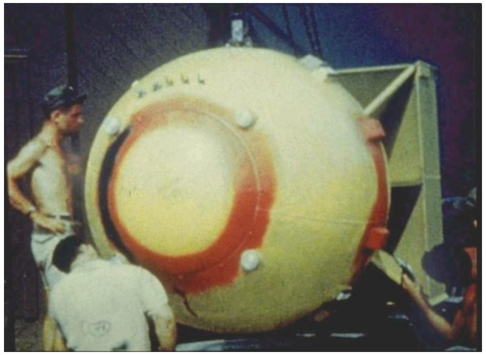
Supercritical mass
(chain reaction accelerates)

Fission Bomb





Uranium bomb "Little Boy" destroyed Hiroshima, Aug. 1945



Plutonium bomb "Fat Man" wiped out Nagasaki, Aug. 1945

Nuclear Attacks WW2

- August 6, 1945: Uranium weapon dropped on Hiroshima. 80,000 dead.
- August 9: Plutonium bomb dropped on Nagasaki. 40,000 dead.
- August 14: Japan surrenders.
- Tens of thousands more die over weeks/months due to radiation effects.

- The explosive yield of nuclear weapons is measured in **kilotons**. One kiloton is the amount of energy released by the explosion of 1000 tons of high explosive (TNT).
- Hiroshima bomb: 12 kilotons. Nagasaki bomb: 22 kilotons.
- **Radioactive fallout**: highly radioactive fission products were spread over a wide area.
- **Tactical** nuclear weapons (drones, artillery shells, rockets): 10 tons to a few kilotons.
- **Strategic** nuclear weapons (bombs, intercontinental missiles): Tens of kilotons to tens of megatons (H-bombs).

Clicker

To sustain a fission chain reaction,

A) Each fissioning nucleus must release a sufficient number of alpha particles.

B) Each fissioning nucleus must release a sufficient number of neutrons.

C) Energy must be continually supplied from outside.

D) The nuclei must collide with enough energy to overcome the electric repulsion between nuclei.

E) All of the above.

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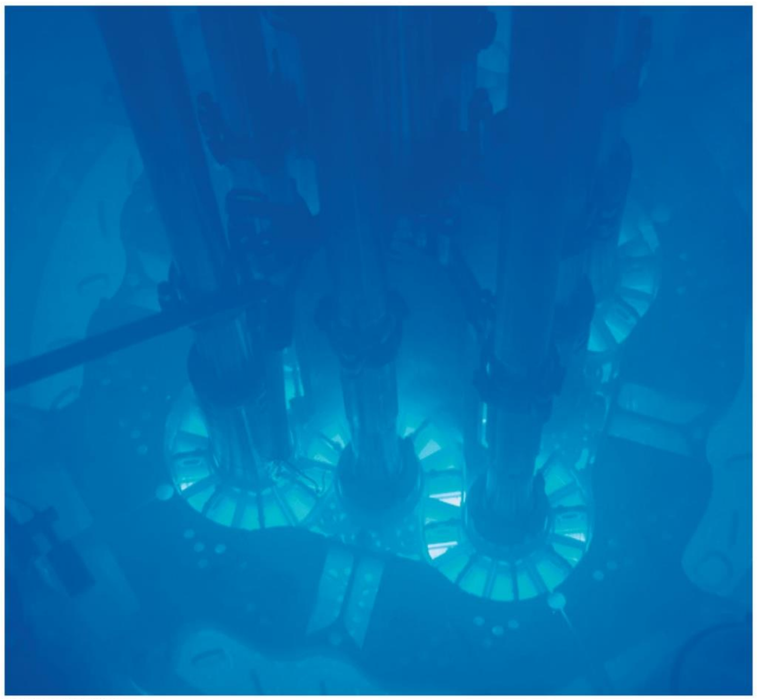
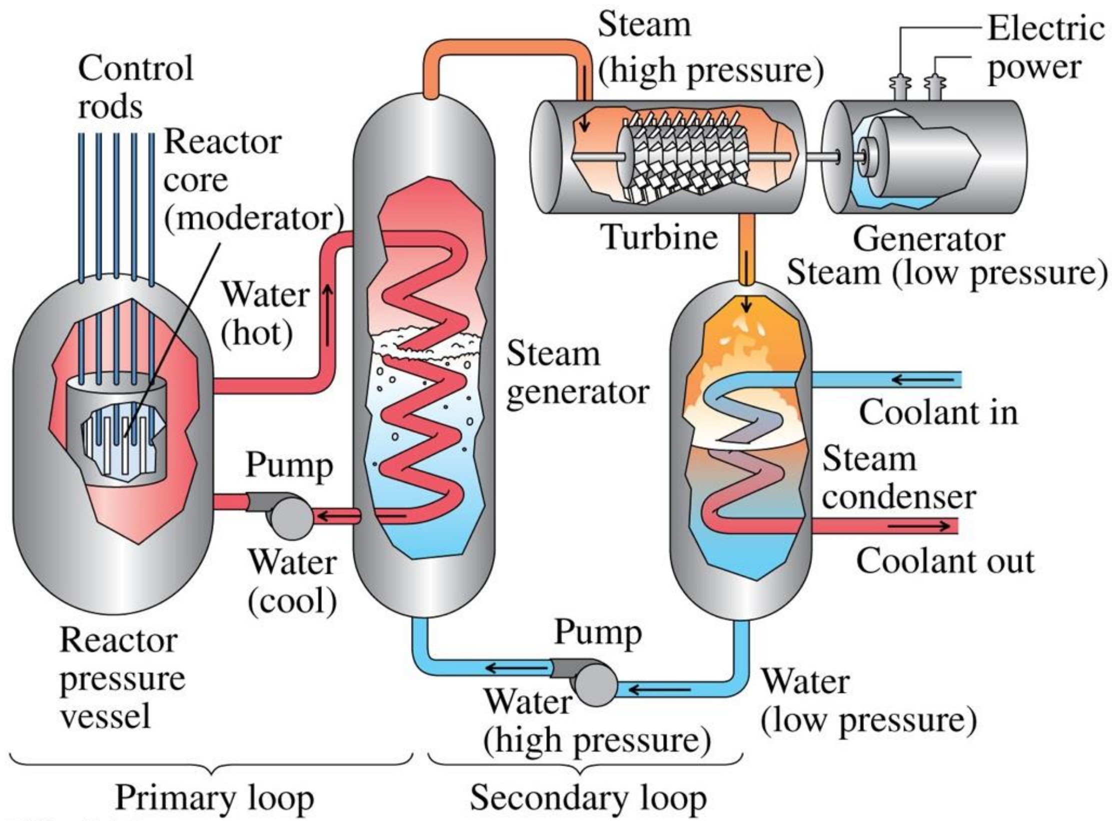
Nuclear Power Reactors

The kinetic energy of the decay products is converted into heat, transported into a heat exchanger, used to turn turbines and generate electricity. The decay elements typically are stopped in the fuel, heating it up. They are cooled by liquid coolant, typically water.





Picture of reactor core. Why is there a blue glow in the water?

Nuclear Power Safety Issues

In the event of an interruption of normal operation, it is not enough to shut down the chain reaction:

- The reaction products are highly radioactive, and the heat generated is enough to melt not only the fuel rods, but the reactor vessel and everything else used to contain the radioactive material ("nuclear meltdown").
- Whenever this happens (Chernobyl 1986, Fukushima 2011) huge amounts of radioactivity are released into the environment.

Spent fuel rods are a huge liability:

- For the first 10 to 20 years they produce enough heat to require constant cooling.
- For the next couple of thousand of years they are radioactive enough to be an extreme hazard for human health and the environment.
- Spent fuel contains fissionable plutonium: Bomb material!
- They need to be constantly guarded (for thousands of years) to prevent them from falling into the hands of terrorists (or anybody, for that matter).

- ➢ These are **externalized costs** (not paid by electric power company, but by society & future generations).
- ➢ If they were included in price of electricity, nuclear power would be much less competitive.
- ➢ Same for fossil fuels and costs of climate change.