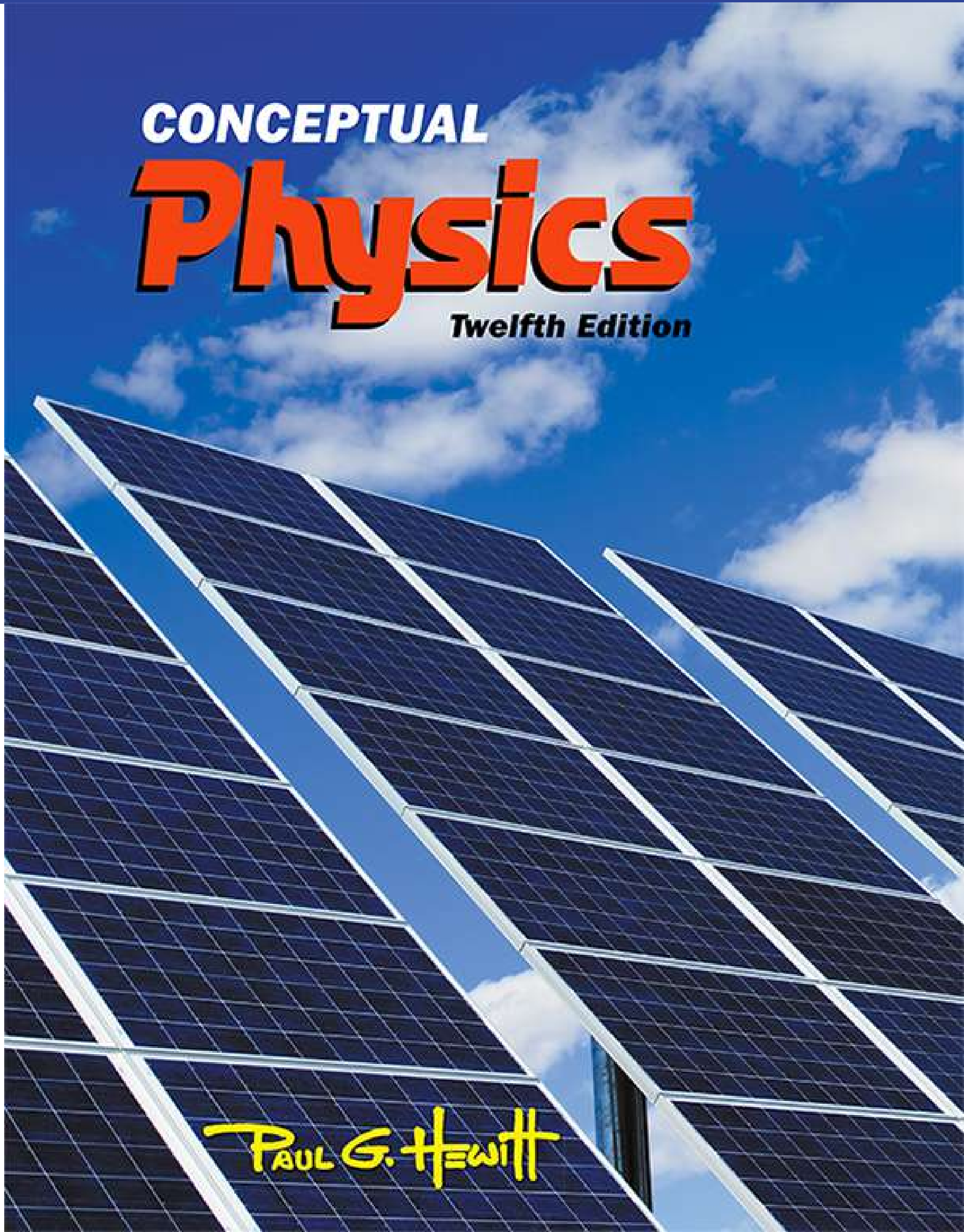
Lecture Outline

Chapter 34: Nuclear Fission and Fusion

Part 2



Mass–Energy Equivalence: $E = mc^2$

- Early in the early 1900s, Albert Einstein discovered that mass is actually "congealed" energy.
- *Equivalence of mass and energy:*
- For a particle of mass m at rest: $E = m \cdot c^2$

where E = energy

m = mass

c^2 = speed of light squared

$= (3 \times 10^8 \text{ m/s})^2 = 9 \times 10^{16} \text{ m}^2/\text{s}^2$

→ Tiny mass can be converted to enormous energy!

Energy released in Hiroshima ≈ 5 g (a nickel)…

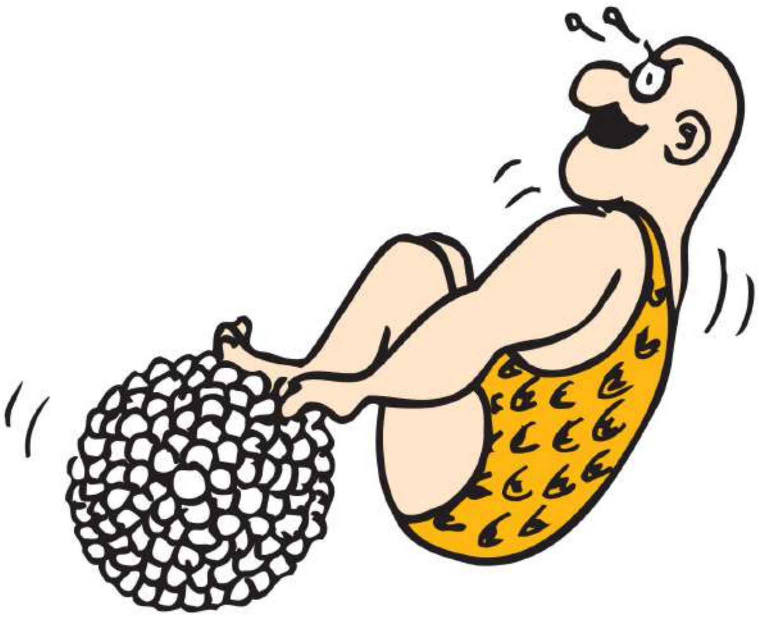
Classwork

18. What celebrated equation shows the equivalence of mass and energy?

Mass–Energy Equivalence: $E = mc^2$

- The more energy stored in a particle, the more its mass.

- Enormous work (force x distance) is required to pull nucleons from a nucleus.
- This work is energy added to the nucleon that is pulled out→ it has more energy



Nucleons (neutrons and protons) have *more mass* when they are by themselves outside of the nucleus.

Classwork

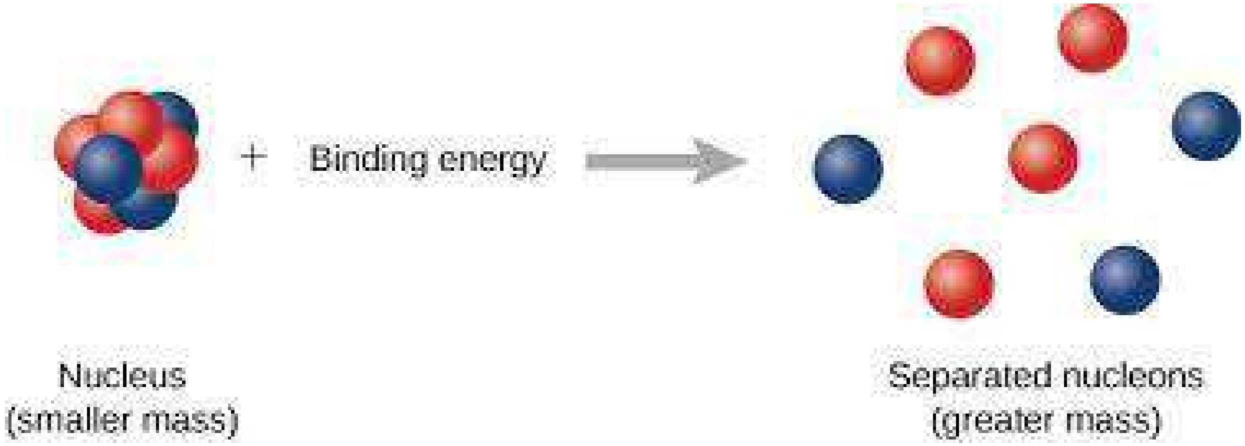
19. Is work required to pull a nucleon out of an atomic nucleus? Does the nucleon, once outside, have more energy than it did when it was inside the nucleus? In what form is this energy?

Binding energy

binding energy = work to disassemble nucleus

$$E = \Delta m \cdot c^2$$

where Δm = nucleus mass – sum of parts

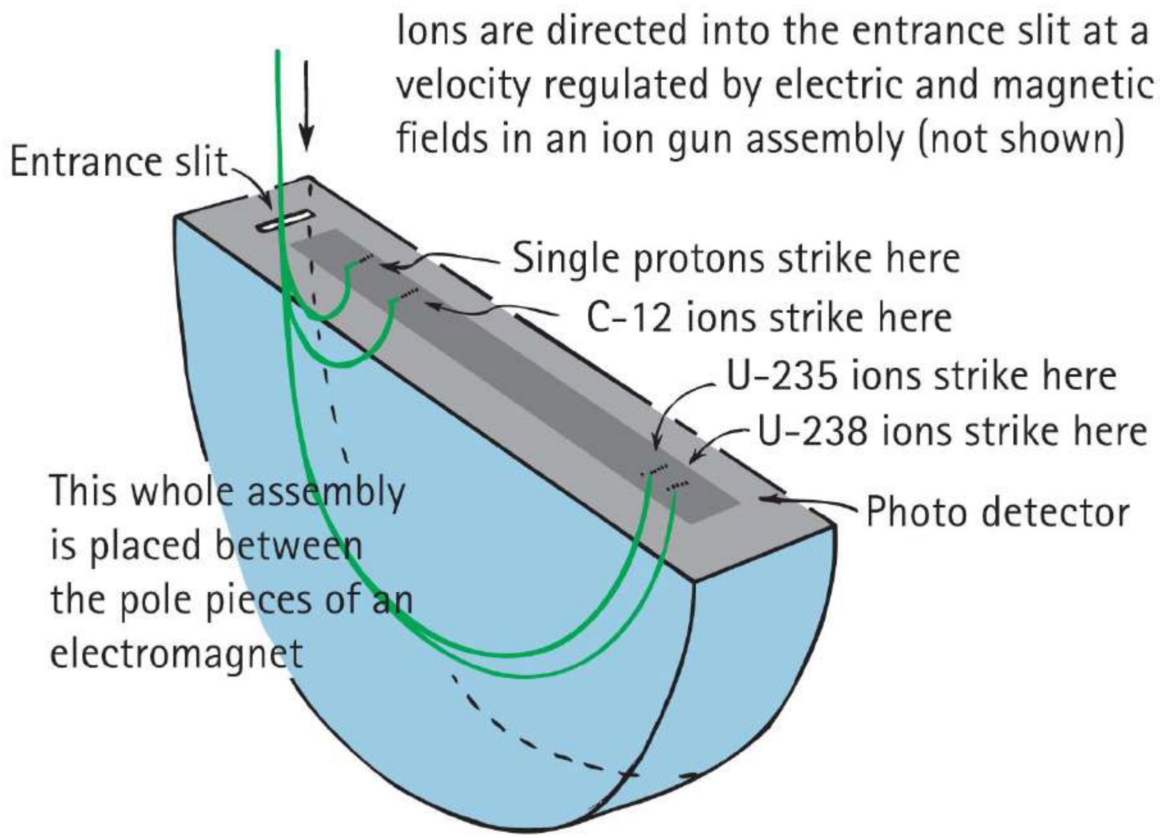


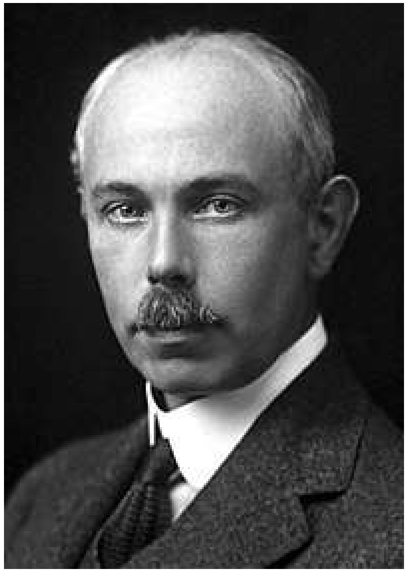
more binding energy → more tightly held particles

→ *less* mass that the particles have when in the nucleus

How to measure mass of nucleus?

- Very precise measurements of atomic mass are made with a mass spectrometer:



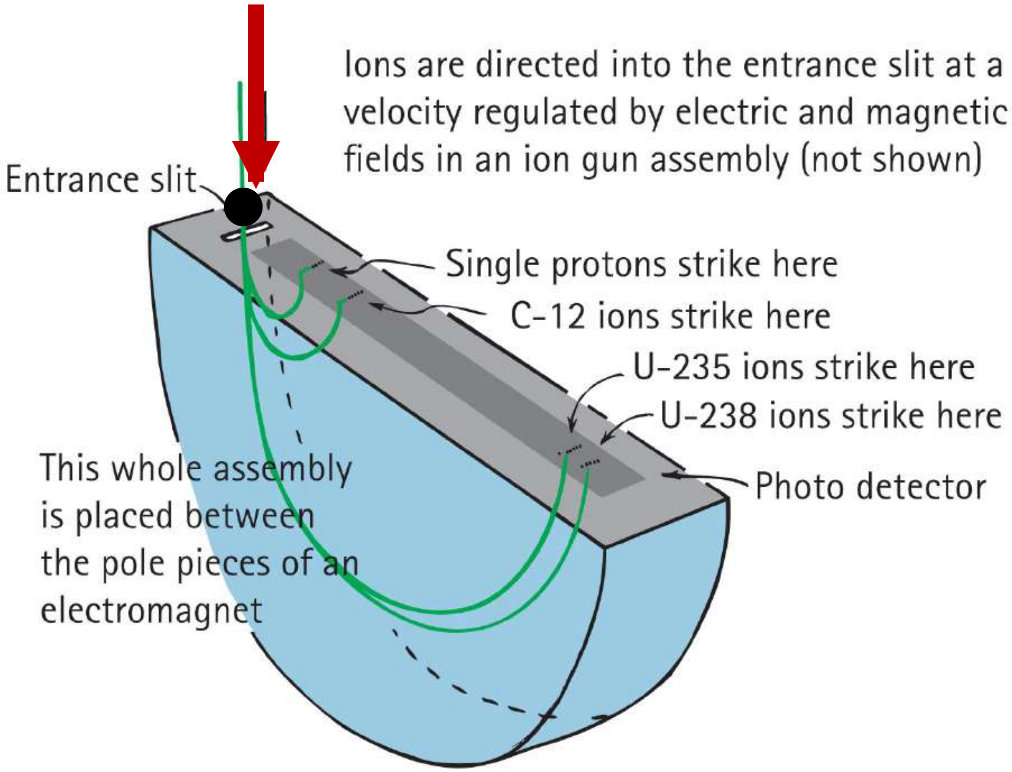


Invented by F.W. Aston

Nobel Prize in Chemistry 1922

Mass Spectrometer

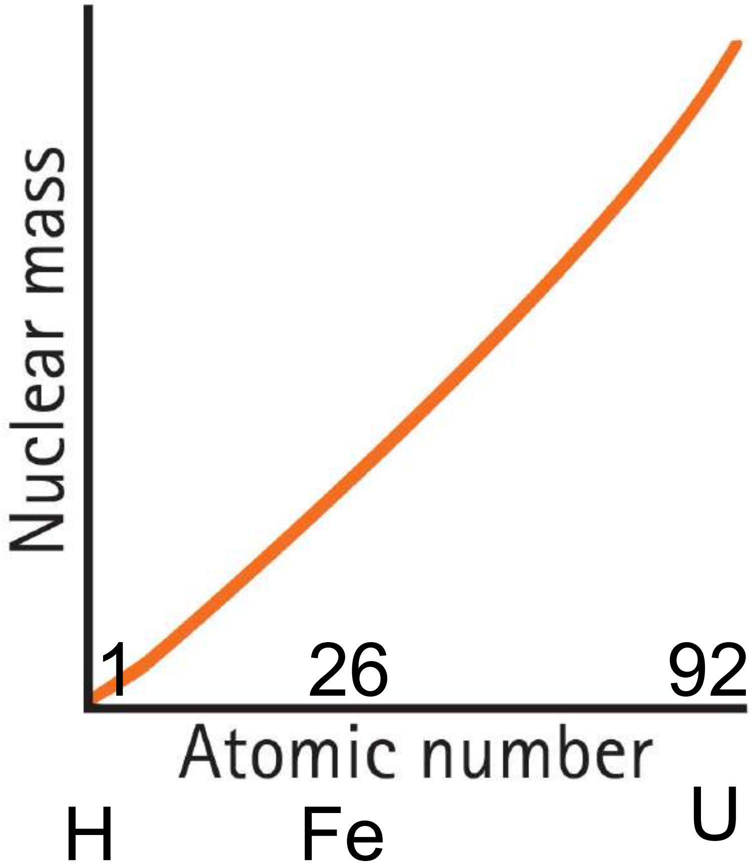
- Electrically charged isotopes are directed into the semicircular "drum. " They are forced into curved paths by a strong magnetic field.
- Lighter isotopes with less inertia (mass) easily change direction and follow curves of smaller radii.
- Heavier isotopes with greater inertia (mass) follow larger curves. Mass of an isotope ~ distance from entrance slit.



Classwork

20. Which ions of like charge and equal speed are least deflected in a mass spectrometer?

- The mass spectrometer is used to find the masses of nuclei for every element (1-92).
- The plot below shows how nuclear mass increases with increasing atomic number.



Surprising?

No. Bigger nuclei have more mass.

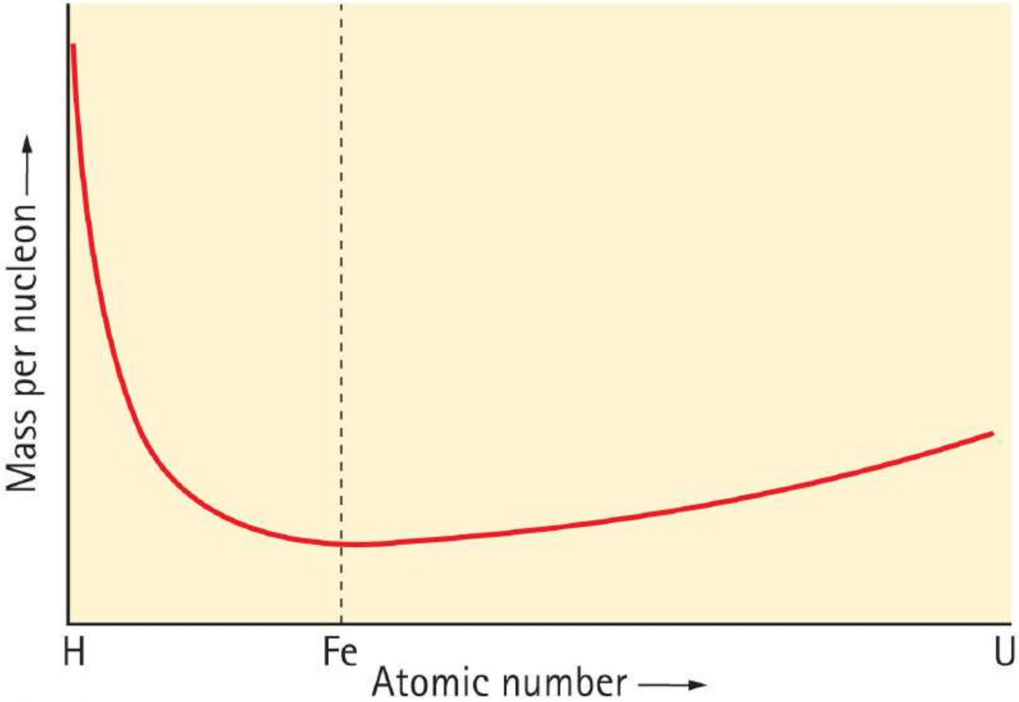
(It curves upward because bigger nuclei have more neutrons.)

But if you divide the mass of each nucleus by the number of nucleons, you get the mass per nucleon:

$$\text{mass per nucleon} = \frac{\textit{mass of nucleus}}{\textit{number of nucleons}}$$

A very important graph results from the plot of nuclear mass *per nucleon* from hydrogen through uranium:

→ **All nucleons do NOT have the same mass!**



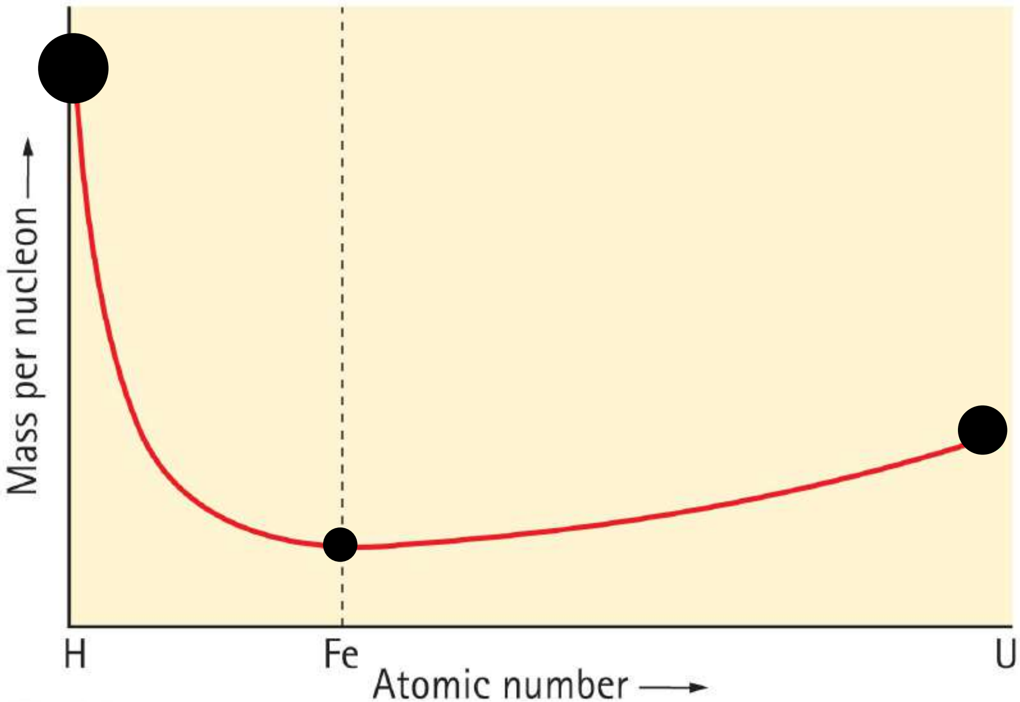
Greatest mass per nucleon → H

→ it has no binding energy

Least mass per nucleon → Fe

→ most binding energy

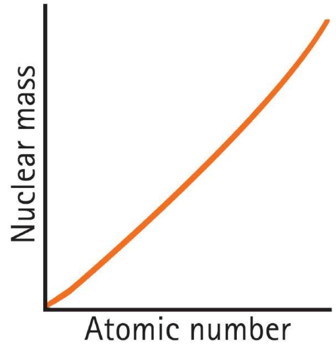
Beyond Fe → mass per nucleon increases up to U

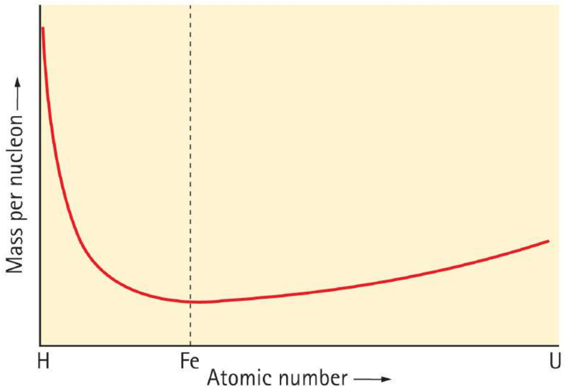


Iron Fe sits at the bottom of a "mass valley."

Classwork

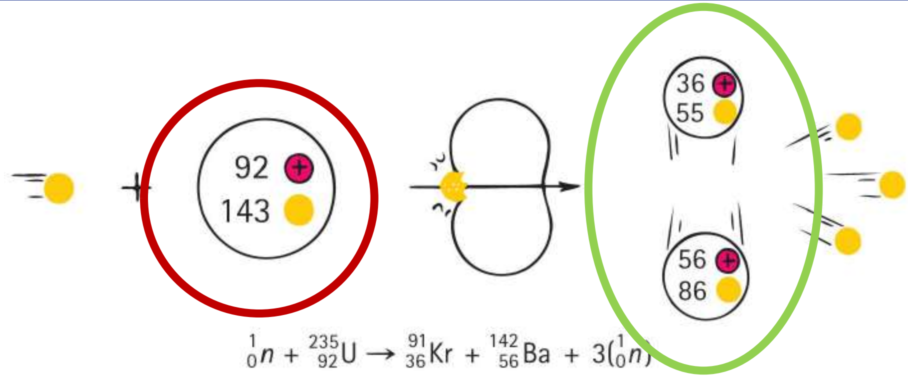
21. What is the basic difference between the graphs in Figure 34.15 and Figure 34.16?

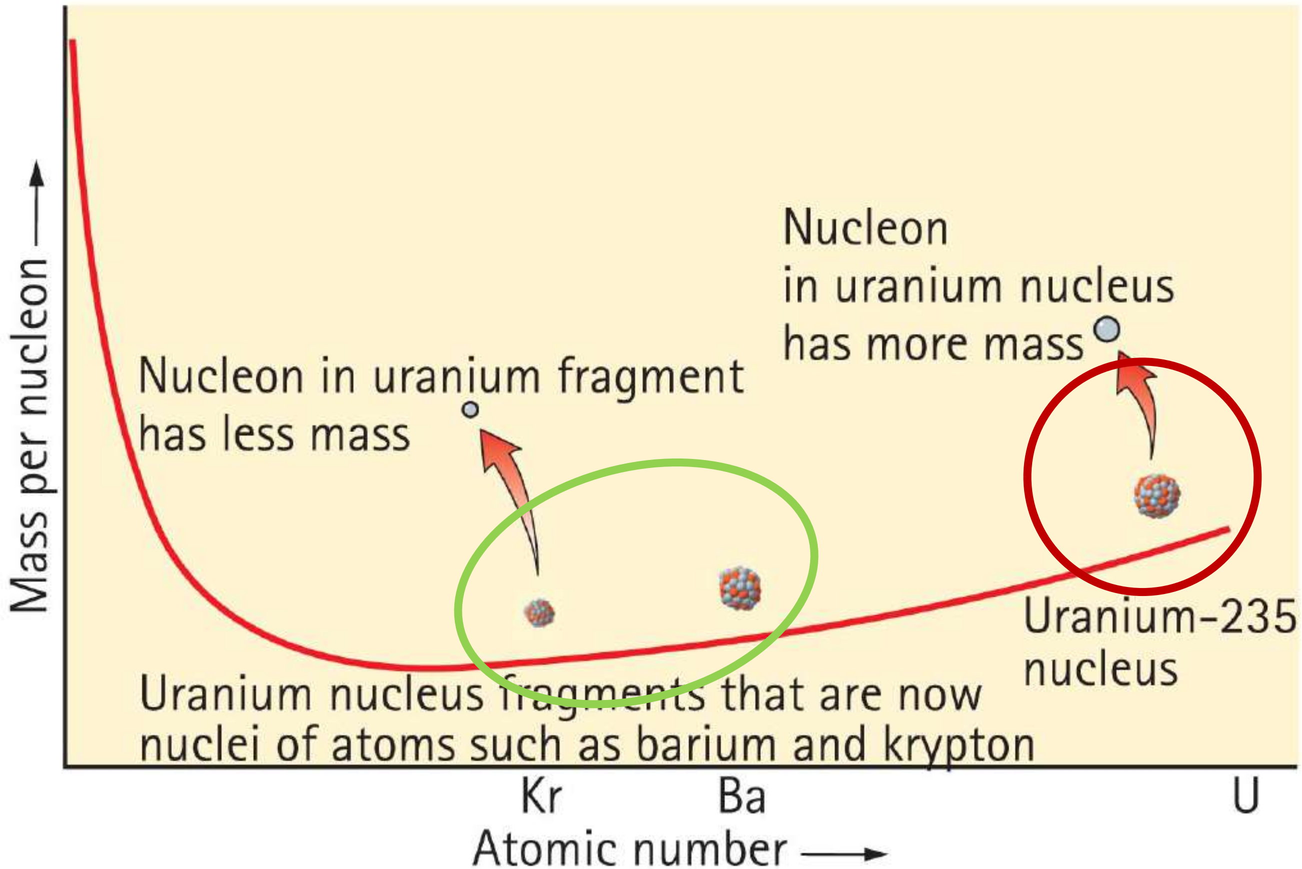




22. In which element is the mass per nucleon greatest? Least?

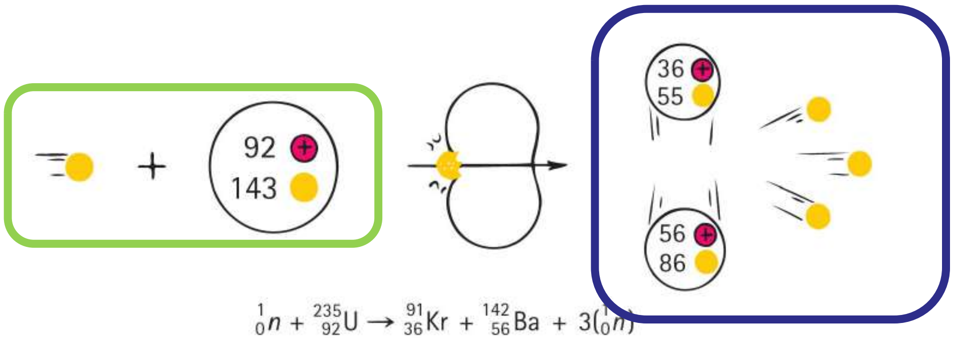
- The same graph, with emphasis on nuclear fission:



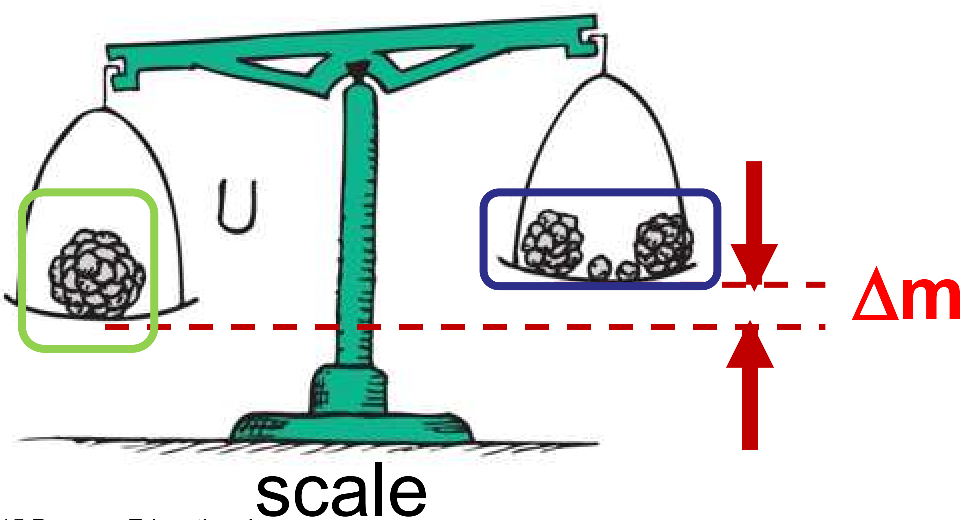


- Is mass gained or lost?

The mass per nucleon in fission products (Kr and Ba) is less than the mass per nucleon of the same nucleons when they are in the uranium nucleus:



Same # of nucleons on both sides!



The mass difference multiplied by c^2:

$E = \Delta m \cdot c^2$

$= 173{,}000{,}000$ eV

= energy released by splitting 1 U atom

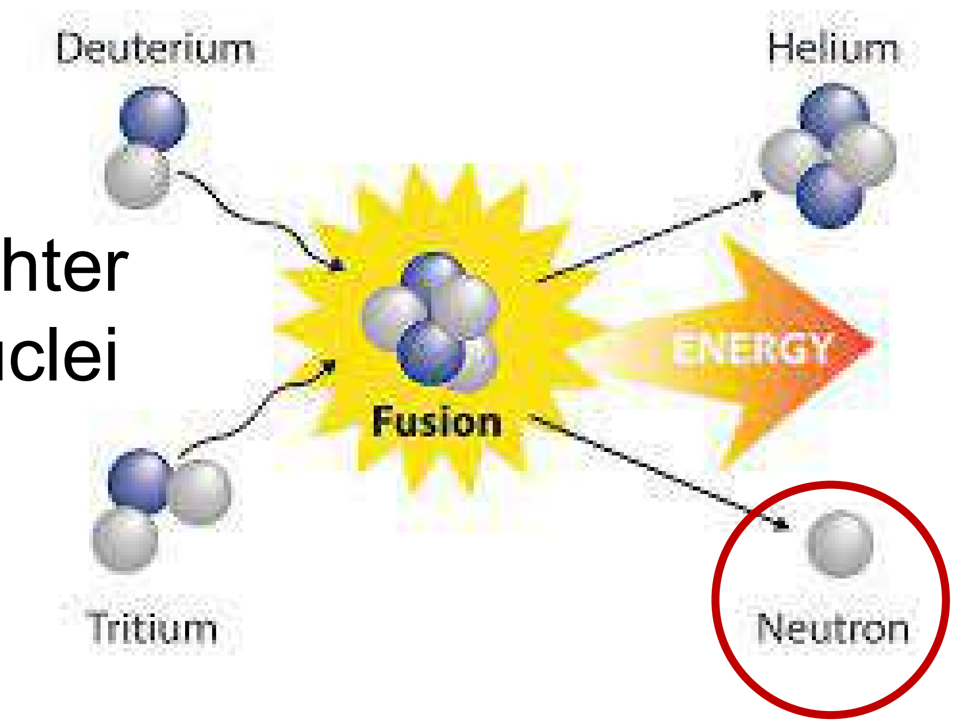
Classwork

23. How does the mass per nucleon in uranium compare with the mass per nucleon in its fission fragments?

Nuclear Fusion:

fusion = when lighter nuclei combine (fuse) together to form heavier nuclei.

lighter nuclei



heavier nucleus

+ γ-rays

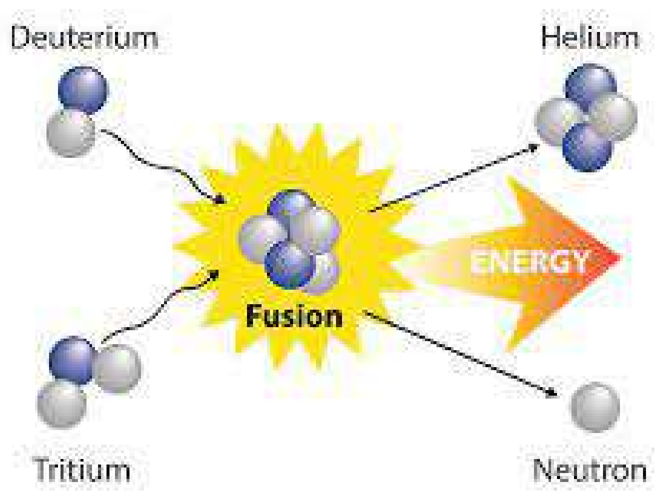
Most of the energy goes into the KE of neutron.

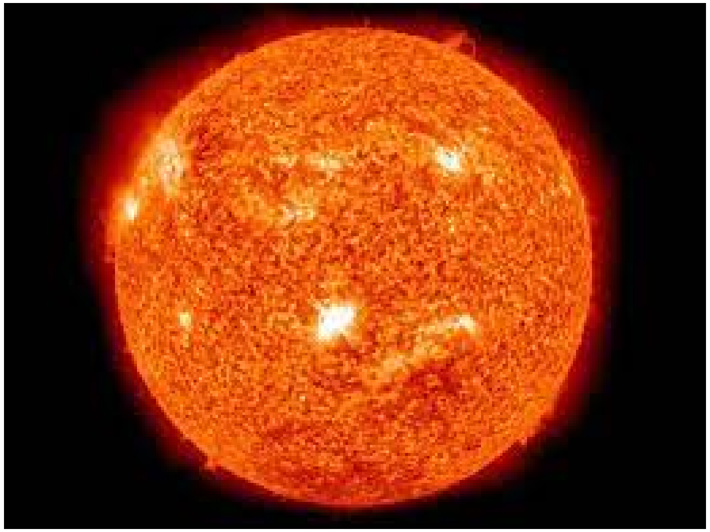
For fusion to occur, the nuclei must collide at very high speeds to overcome the electric repulsion.

Once close, the strong nuclear force binds them.

These high speeds require high temperatures.

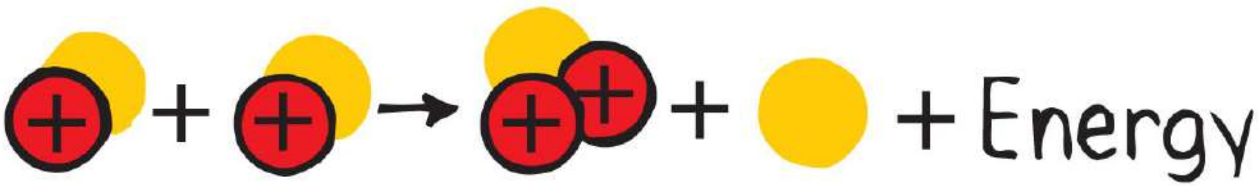
Such temperatures are found in the core of the Sun and stars.





This is called *thermonuclear* fusion.

- Typical fusion reactions:



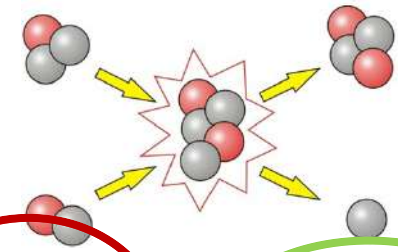
$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.26\ MeV$$

SMALLER particles → **BIGGER particle** (+ neutron)

→ So what mass is converted to energy?

Same graph as before but emphasis on Nuclear Fusion:

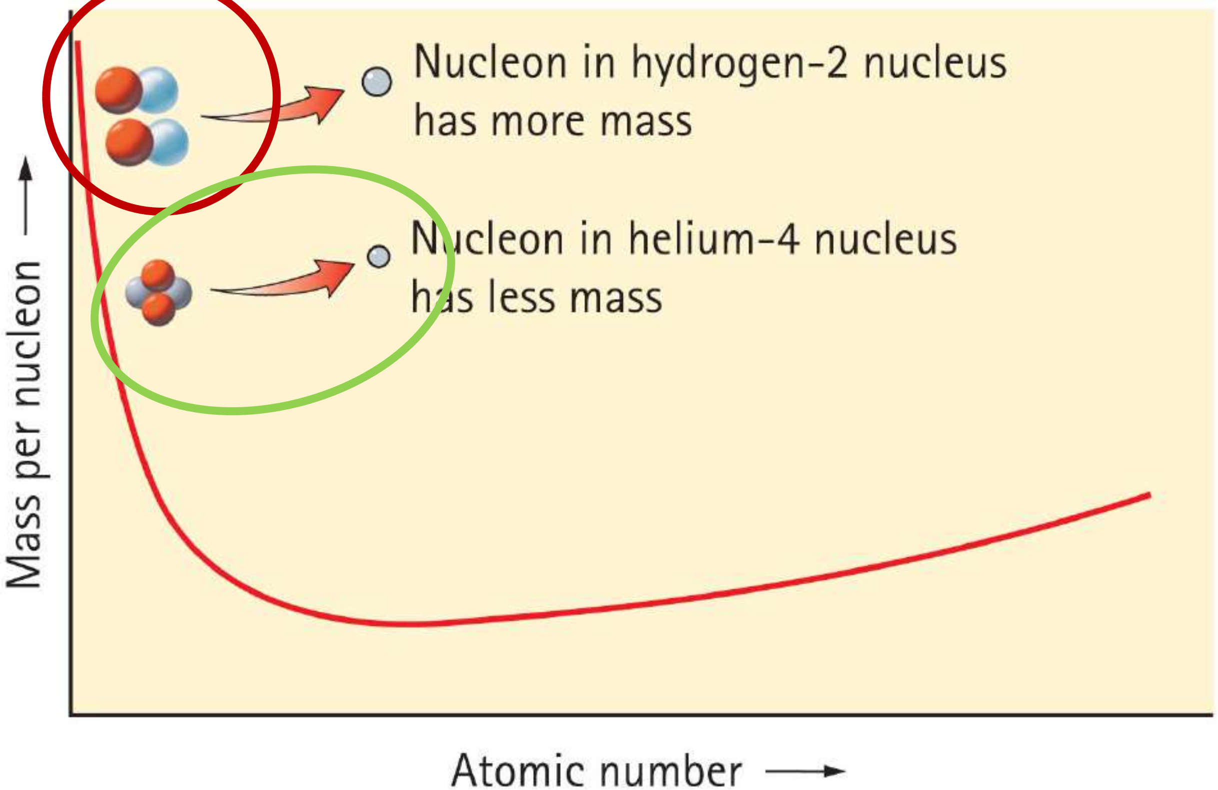
Same number of nucleons on both sides of the equation:



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

more mass *per nucleon*

less mass *per nucleon*

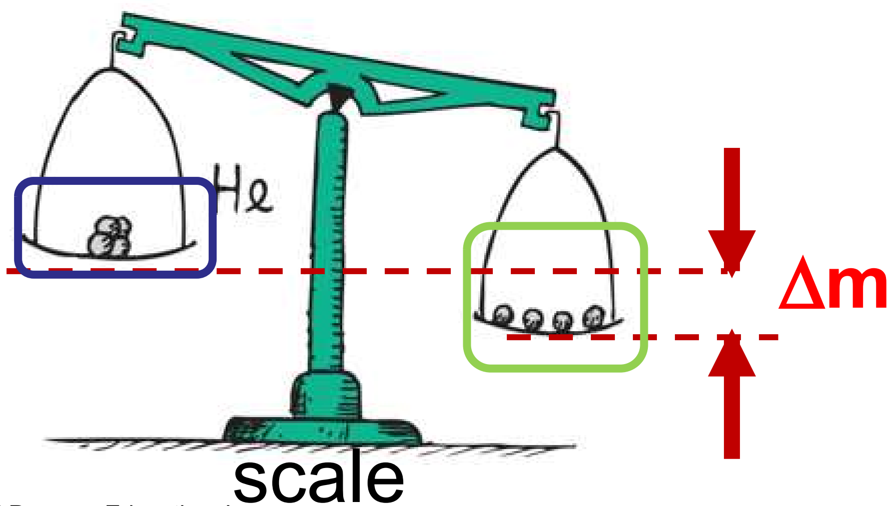


Using fusion, the Sun converts **4 million tons of mass** to energy ***every second*.**

The mass per nucleon in fission product (He) is less than the mass per nucleon of the same nucleons when they are in H.

Basic reaction is: **4 protons → He**

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



The mass difference multiplied by c^2:

$E = \Delta m \cdot c^2$

$= 18{,}000{,}000$ eV

= energy released by fusing 1 He atom

Classwork

26. When a pair of hydrogen nuclei are fused to create helium, how does the mass of the resulting helium nucleus compare with the sum of the nuclear masses before fusion?

27. For helium to release energy, should it be fissioned or fused?

Fusion vs. Chemical Combustion (burning)

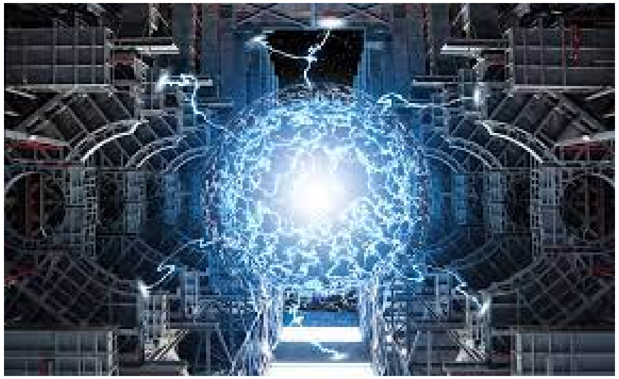
Both fusion and chemical combustion have the following in common:

- high temps needed to start
- release of energy helps maintain process
- particles end up more tightly bound

    burning: atoms combine to molecules

    fusion: nuclei combine to other nuclei

- mass decreases as a result



- Main difference:

→ **More energy with fusion**

Fission vs fusion

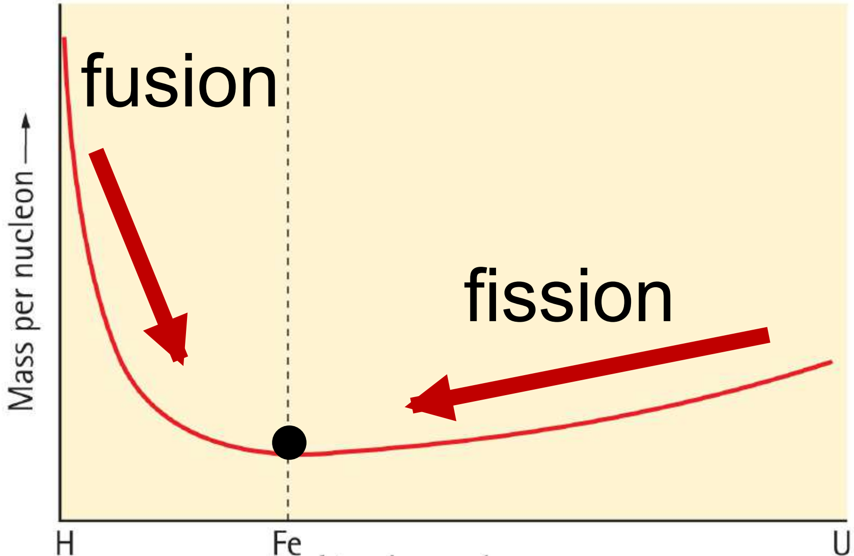
- Less mass per nucleon occurs in *both* processes.
- "Missing" mass becomes energy for *both*.

Both processes move towards lower energy:

But **in fusion:**

→a higher % of mass converted to energy

→ more efficient



Classwork

24. What becomes of the "lost" mass per nucleon in fission and fusion reactions?

25. If the graph in Figure 34.16 is seen as an energy valley, what can be said about the energy of nuclear transformations that progress toward iron?

Nuclear Fusion
CHECK YOUR NEIGHBOR

When a fusion reaction converts a pair of hydrogen isotopes to an alpha particle and a neutron, most of the energy released is in the form of

A. gamma radiation.
B. kinetic energy of the alpha particle.
C. kinetic energy of the neutron.
D. All of the above about equally.

Nuclear Fusion
CHECK YOUR ANSWER

When a fusion reaction converts a pair of hydrogen isotopes to an alpha particle and a neutron, most of the energy released is in the form of

C. **kinetic energy of the neutron.**

Explanation:

By momentum conservation, the ejected neutrons have a high speed compared with the alpha particle, and therefore much kinetic energy. It is the kinetic energy of the neutrons that becomes the heat needed for power. Gamma rays play a small energy role, as they do in fission.

Dropping F (fission and fusion) Bombs

The high temperatures needed to start fusion are provided by exploding a fission bomb first.

Fission bombs:

Critical mass limits size.

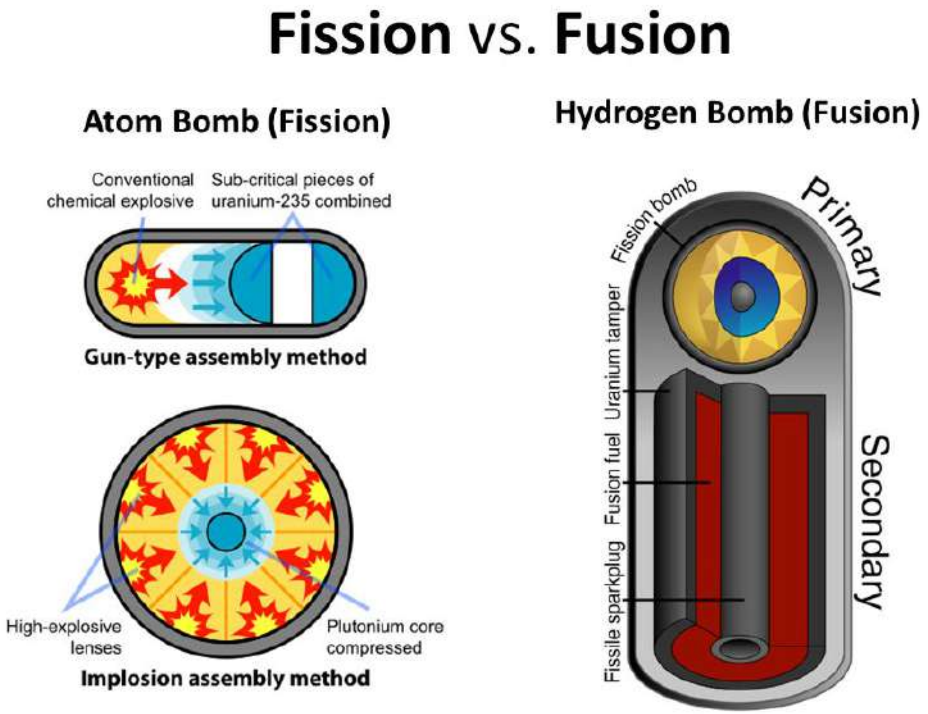
Called atomic bombs.

Fusion bombs:

No limit on size.

Called "H" bombs or thermonuclear bombs.

Never used in warfare.

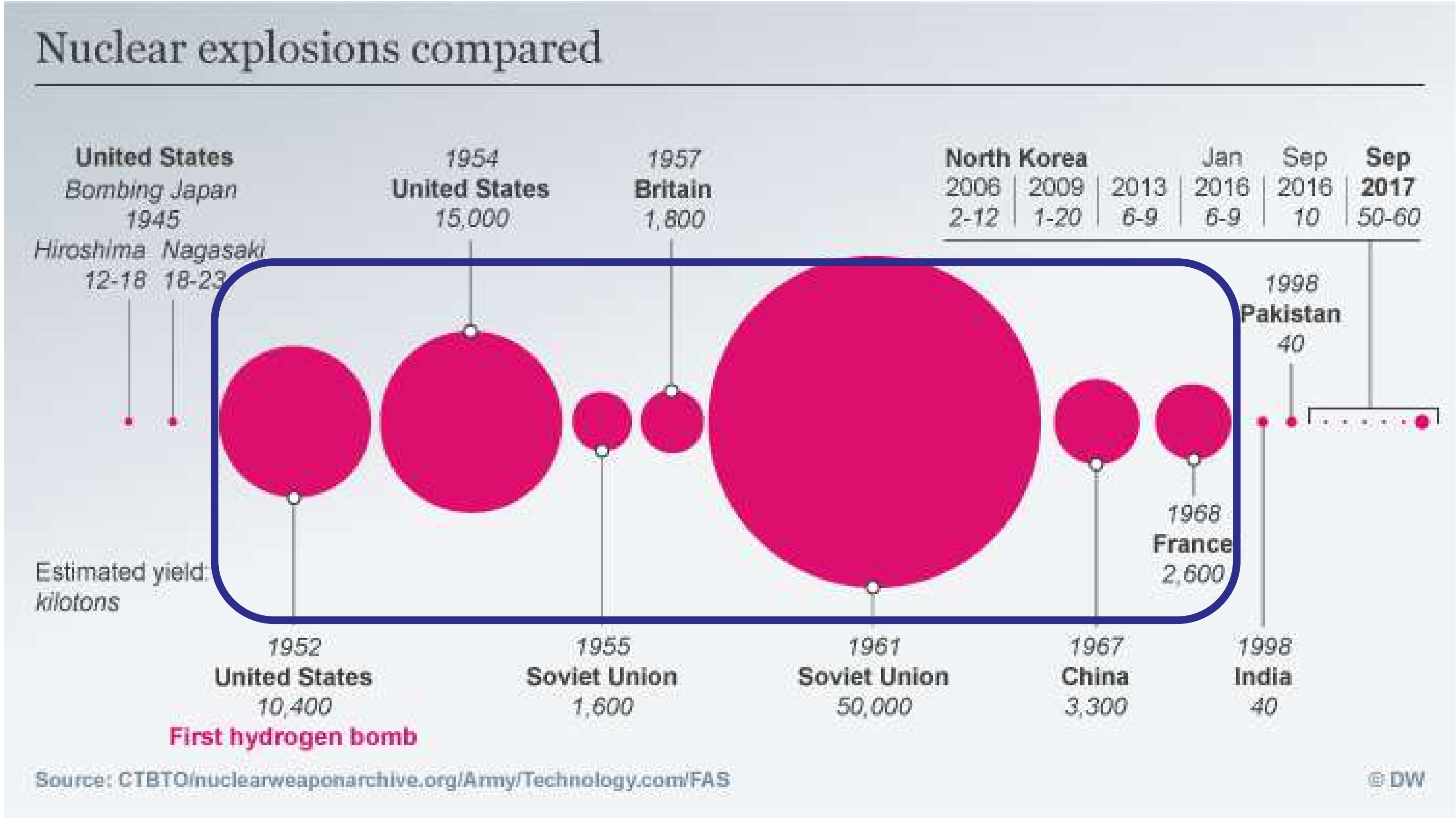


Explosive power of nuclear bombs:

Units are tons of TNT (a chemical explosive):

Fission bombs: usually in kilotons = 1000 tons

Fusion bombs: usually in megatons = 1000 kilotons



Thermonuclear bombs ≈ 1000x atomic bombs

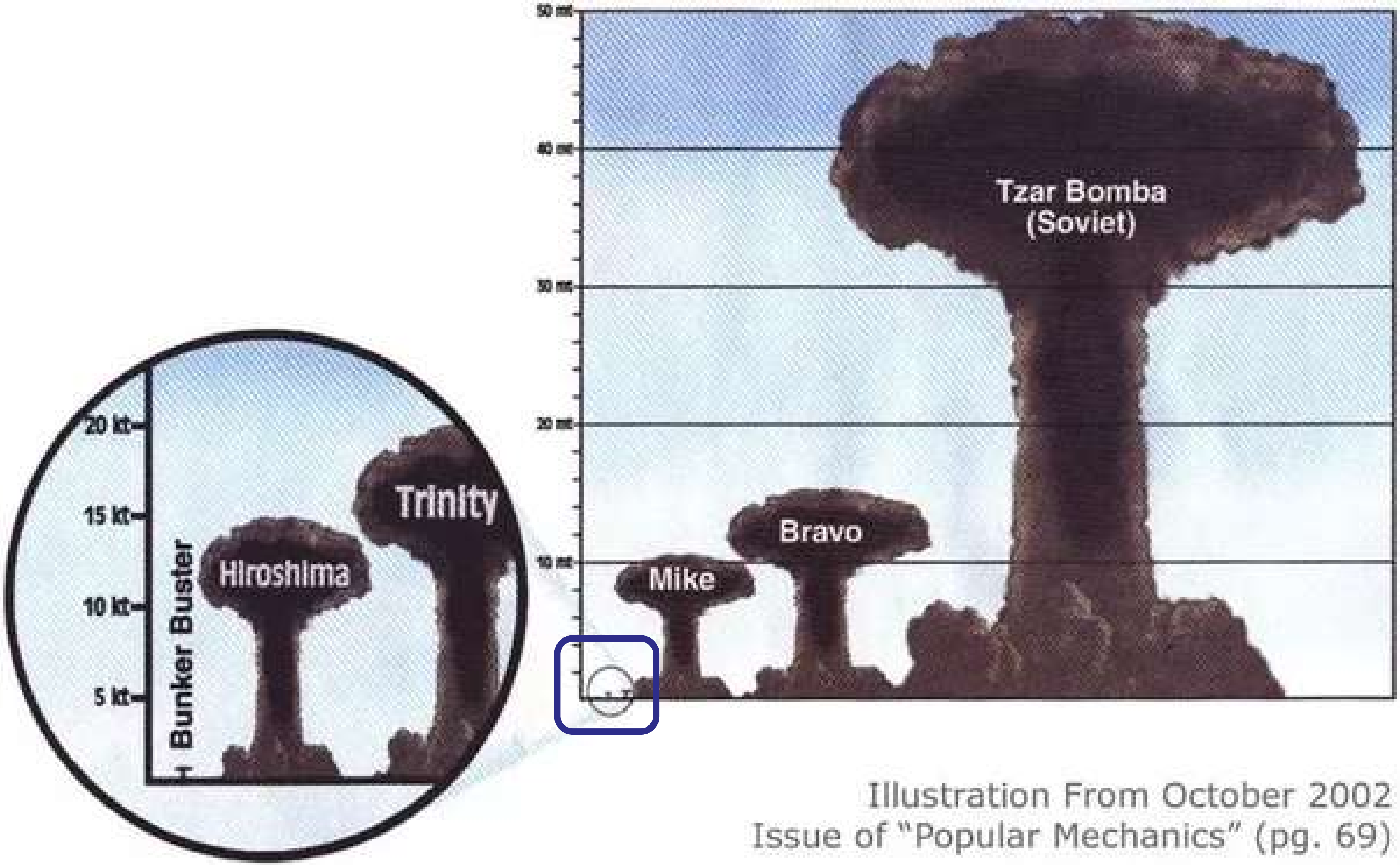


Illustration From October 2002
Issue of "Popular Mechanics" (pg. 69)

Controlling Fusion

- Fusion could provide a safer energy source.
- The fuel: H is the most plentiful in universe
- Best reaction at moderate temps:

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

$^{2}_{1}H$ = deuterium = found in ordinary water

$^{3}_{1}H$ = tritium = almost nonexistent but can be made

→ Carrying out controlled fusion is more difficult than thought when fission succeeded.

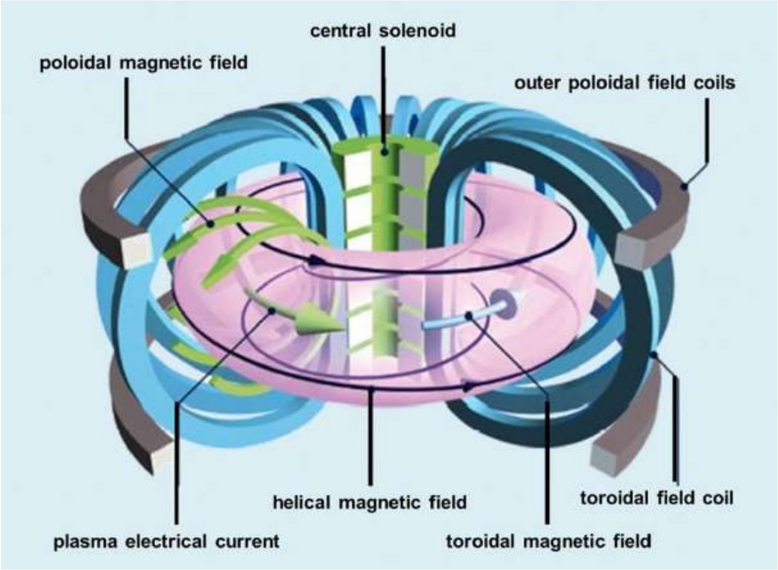
→ One problem is containing the high temperatures needed for fusion.

Classwork

28. What isotopes of hydrogen fuse best at "moderate" temperatures?

29. Which isotope of hydrogen—deuterium or tritium—is abundant and which is scarce?

Controlling Fusion



Plasma reactors have not been successful….yet.

ITER ("the way") in France uses a **tokamak** *(**то**роидальная **ка**мера с **ма**гнитными **к**атушками)* to contain a fusing plasma in a donut-shaped magnetic field.

It is the most expensive science experiment ever.

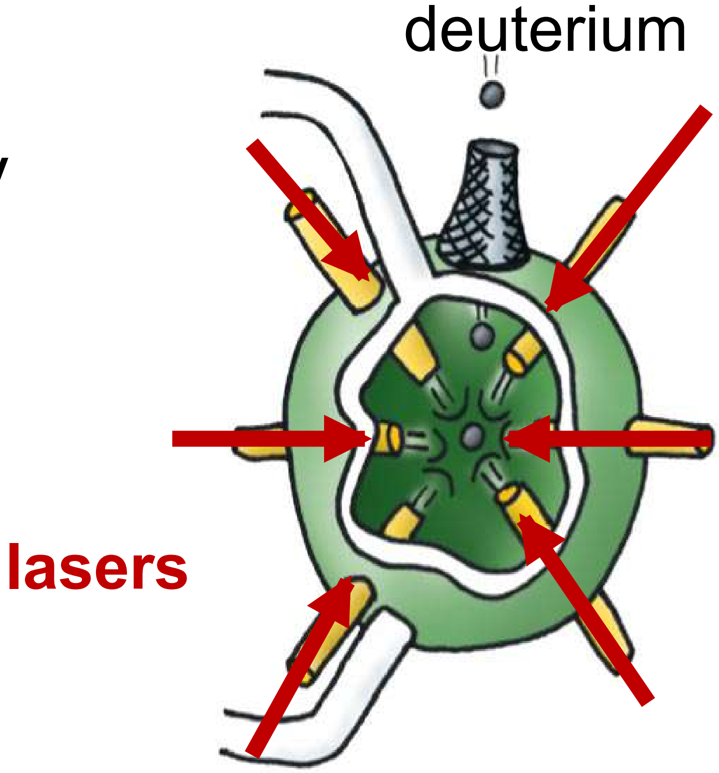
Started in 2013, run by 7 countries, and due to come online in 2025-2035.

Controlled fusion:

Other schemes, including lasers, are being considered:

Deuterium pellets rhythmically dropped into synchronized laser crossfire:

Heat used to produce steam.



→ There are no working fusion reactors yet.

Nuclear Fission
CHECK YOUR NEIGHBOR, Continued-4

In either a fission event or a fusion event, the quantity that remains unchanged is

A. energy.
B. the mass of nucleons.
C. the number of nucleons.
D. None of the above.

Nuclear Fission
CHECK YOUR ANSWER, Continued-4

In either a fission event or a fusion event, the quantity that remains unchanged is

C. **the number of nucleons.**

Explanation:

This is a premise of reaction equations, whether nuclear or chemical. Although energy and mass undergo changes, the number of particles and amount of charge remain unchanged.

Classwork

30. What kind of nuclear power is responsible for sunshine?