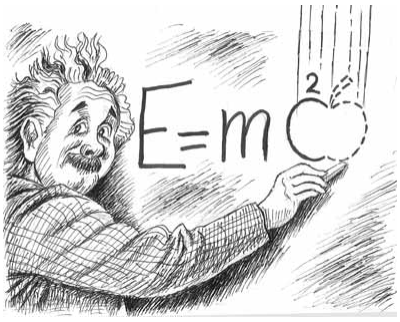
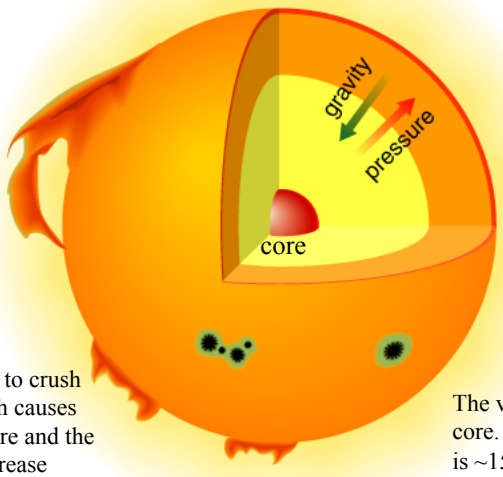
Einstein's Energy Mass Equivalence Powers the Sun!



A Star a balance between gravity and pressure



Gravity tends to crush the star, which causes the temperature and the density to increase toward the center.

The very center is called the core. In the core the density is ~150 times that of water and the temperature is 15 million degrees Kelvin

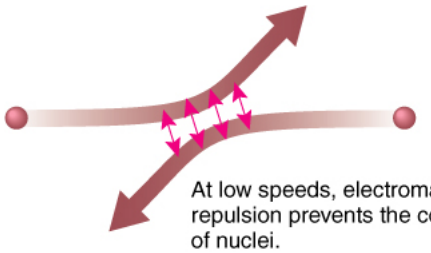
Coulomb Barrier:

The electromagnetic force of repulsion between nuclei of similar electric charge.

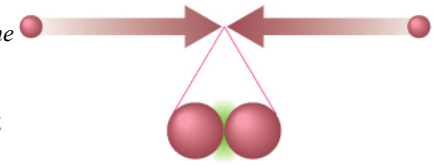
Particles must collide at high speeds to over come this repulsion (barrier). Once they over come it, they bind together using the strong nuclear force.

This is called nuclear fusion. It is the process of building light nuclei into heavier nuclei. *Energy is released in the process.*

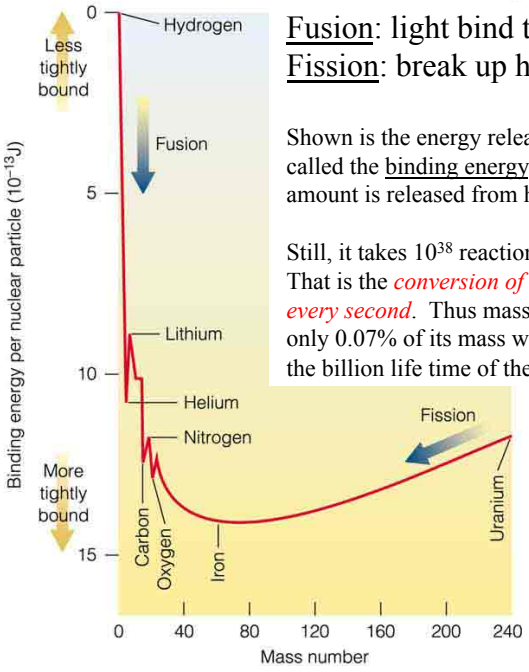
Nuclear fusion is the energy generating mechanism that keeps stars shining.



At low speeds, electromagnetic repulsion prevents the collision of nuclei.



At high speeds, nuclei come close enough for the strong nuclear force to bind them together. Releases Energy.



Fusion: light bind together to form heavy
Fission: break up heavy to form light

Shown is the energy released per fusion/fission event; this is called the binding energy. Note that a relatively large amount is released from hydrogen to helium.

Still, it takes 10^{38} reactions per second to support the sun! That is the *conversion of 5 millions tons of mass into energy every second*. Thus mass is lost from the sun forever. Still, only 0.07% of its mass will be lost this way (added up over the billion life time of the sun).

Note the special location of iron. We revisit this later in Ch 10.

Nuclear Fusion

The bottom line

$$4\ {}^{1}H \longrightarrow {}^{4}He + \text{energy}$$

^{1}H = hydrogen (proton)
^{4}He = helium-4 (alpha particle)

Four hydrogen are fused into a single helium. Energy is released in the process.

Einstein's Famous Mass Energy Equivalence Principle

$$E = mc^2$$

.Energy, E, equals mass, m, times the speed of light square, c^2.

The energy released in nuclear fusion comes from mass! Some mass is lost in each reaction and that amount of mass multiplied by the speed light squared is the energy released in that one reaction.

Computing the Amount of Energy Generated

For a **single net reaction**, four hydrogen are converted into a single helium. The sum of the masses of the four hydrogen does not equal the mass of the helium… some mass "disappeared".

We compute the amount of mass that disappeared and then using *Einstein's energy-mass equivalence*, we can compute how much energy is released (into the star).

Masses of hydrogen and helium are…

1 hydrogen = 1.673 mass units
1 helium = 6.645 m.u.

Mass of four hydrogen is…

4 hydrogen = 4 x 1.673 = 6.693 m.u.

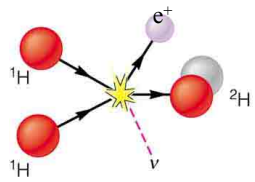
The energy, E, generated is… $E = mc^2$

m = 4 hydrogen – 1 helium = 6.693 - 6.645 = 0.048 m.u.

c = 300,000 km/s

$$E = mc^2 = 0.048\ x\ (3 \times 10^8)^2 = 4.3 \times 10^{15}$$

Step 1 of the Proton-Proton Chain…



$^1H + {}^1H \longrightarrow {}^2H + e^+ + \nu$

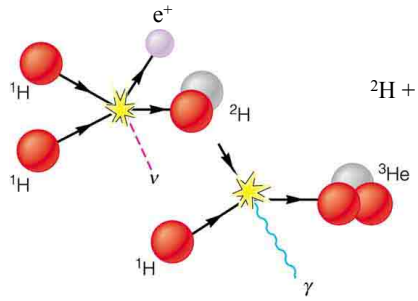
Two hydrogen ions (^1H) "collide". They stick together, or fuse, into **deuterium** (^2H) . Deuterium is an isotope of hydrogen- it has one proton and one neutrino. Basically, one neutron turns into a neutron while releasing a positron and a neutrino. Note that total electric charge is conserved

This is called **fusion**. In the process the **positron** (anti-matter version of electron) finds a free electron in the sun's core plasma and when they collide they annihilate and release energy (photons).

Also, in the process, a **positron** (e^+, antimatter of electron) and a **neutrino** (ν) are produced.

The creation of the neutrino uses the **weak nuclear force**, which is responsible for radioactive decay.

Step 2 of the Proton-Proton Chain…



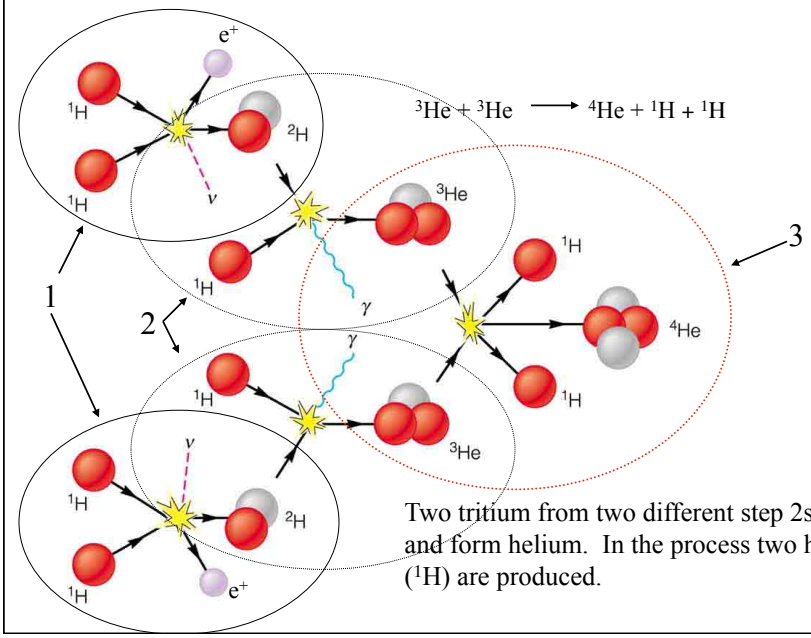
$^2H + {}^1H \longrightarrow {}^3He + \gamma$

The deuterium from step 1 collides with a hydrogen, forming **tritium**.
Tritium is an isotope of helium, with only one neutron instead of the typical two.

In the process, a photon (γ) is produced. This photon carries away energy.

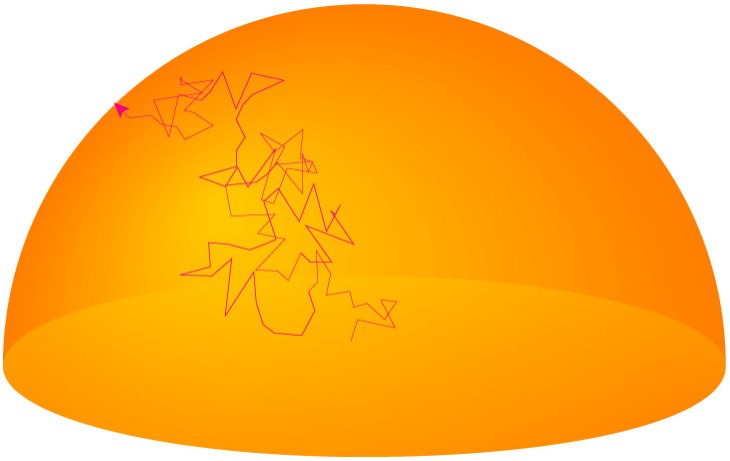
Again, the positron annihilates with a free electron and release energy (photons).

Step 3 of the Proton-Proton Chain…

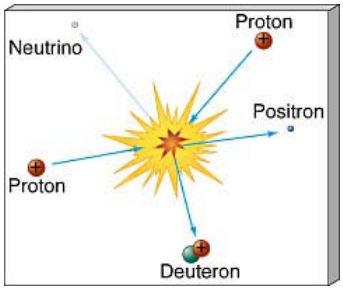


Two tritium from two different step 2s collide and form helium. In the process two hydrogen (^1H) are produced.

A photon created in the core takes 1 million years to surface.



What about those pesky neutrinos…?



Neutrinos arise from the weak nuclear force and are a product of the process that changes one of the protons (+1) into a neutron (0) and a positron (+1).

Neutrinos pass right out of the sun… so they escape sun and provide direct view of sun's core! **About 1,000,000,000,000 neutrinos pass through your body every second** and none of them interact! They can pass through a light year of lead.

If we could measure them (count them per unit time), we could test our theory of the nuclear reactions in the sun.

Well, we found that there are 1/3 as many neutrinos at the earth than Were expected… This is called the **solar neutrino problem.**

A solar neutrino telescope!

C_2Cl_4 cleaning fluid supposed to detect 1 per day, but it found only one every 3 days! We thought we did not understand the sun!!!! Turned out that neutrinos change from one particle to another and leave only 1/3 as many.

NEUTRINO PROBLEM SOLVED! New Physics!