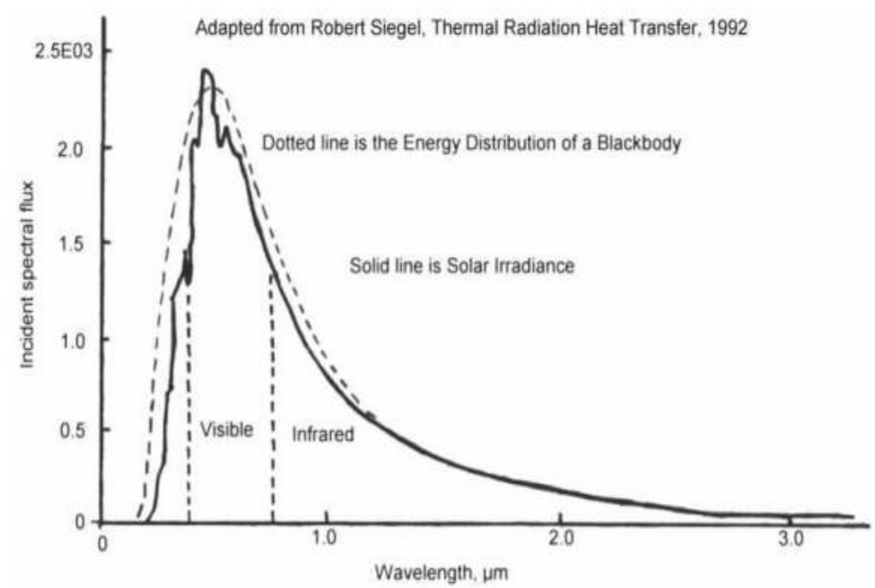
The Sun

Some Properties

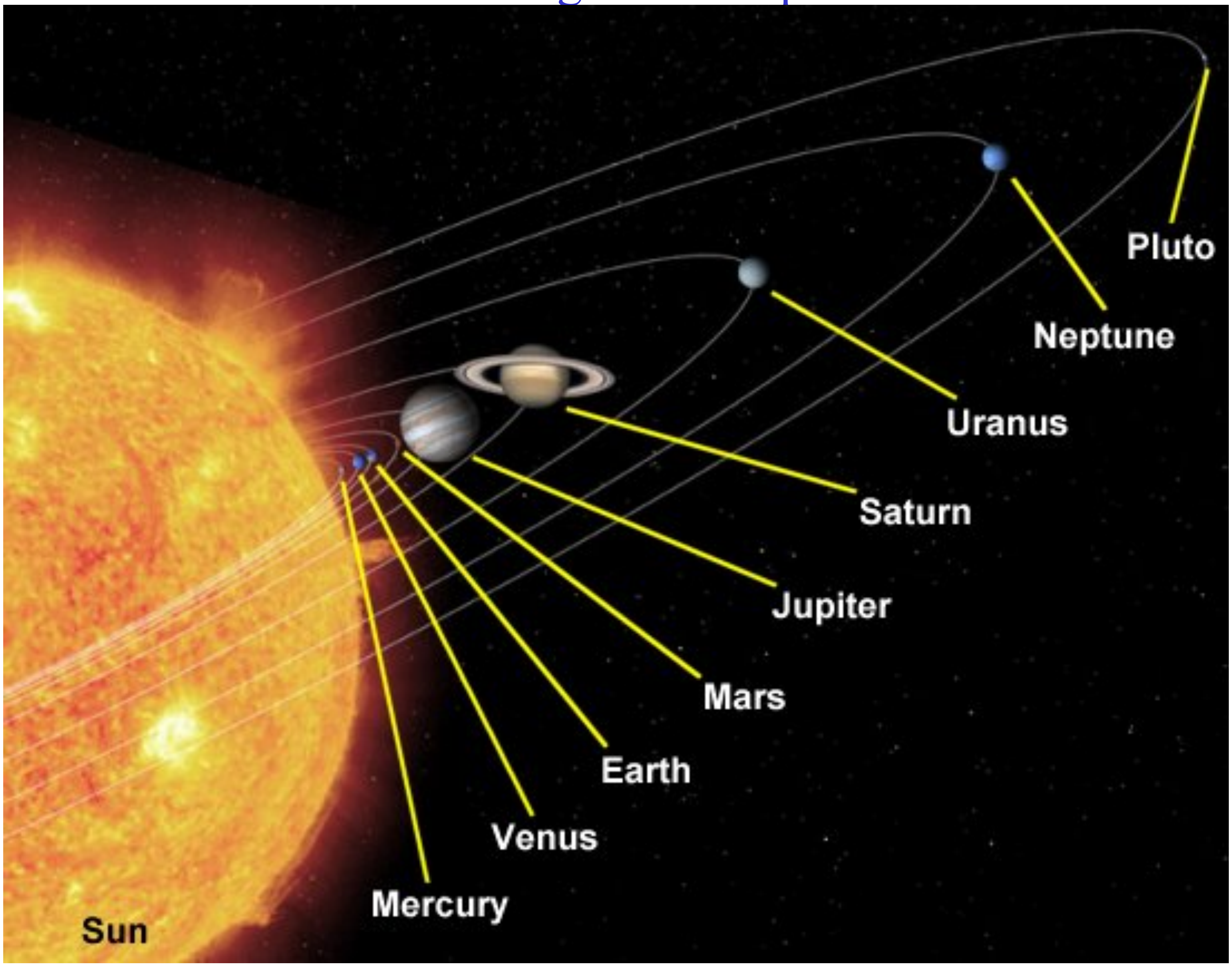
- Diameter - 109 times Earth's
- Volume - about 1,000,000 times Earth's
- Mass - about 300,000 times Earth's 99.8% of Solar System
- Density = Mass/Volume = 1.4 g/cm^3

The Sun is a gas cloud of mostly Hydrogen and Helium

- Surface Temperature = 5,800° K
- Core Temperature = 15,000,000°
- Age about 5 billion years



Sun’s volume ~1,000,000X larger then Earth and ~1,000X larger then Jupiter



Energy Production in the Sun

Sun produces

2 calories/cm^2/minute at Earth's surface

10^{11} cal/minute entire Earth's surface

10^{27} calories/minute entire Sun's surface

Energy produced in the Sun flows out as light (and other EM energy).

Equivalent energy units:

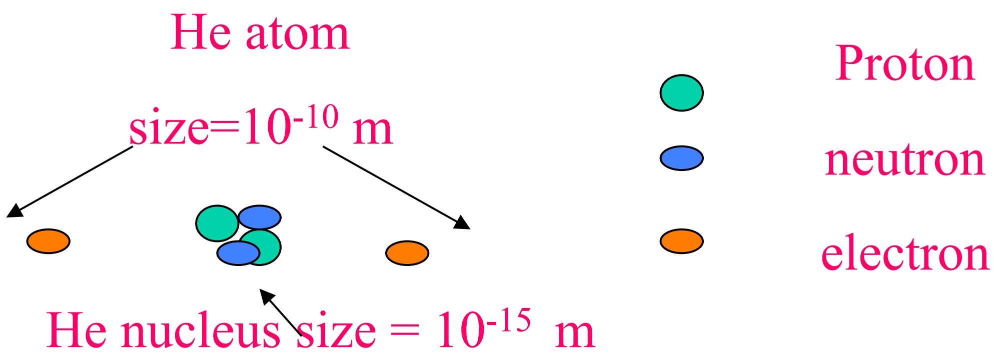
4 times 10^{26} Watts

100 billion 1 Megaton Hydrogen bombs every second

Source of Sun's Energy

- Big mystery before 1940
- Chemical Reactions do not give enough energy
- Gravitational energy can produce about 100 million years at the Sun's output but geological evidence shows Earth is billions of years old
- Need nuclear forces and reactions to power Sun. In particular, the strong nuclear force which holds protons and neutrons together

Atom = Nucleus + Electrons



Some common atoms

Isotopes of hydrogen: Hydrogen, Deuterium, Tritium

	#e	#p	#n
Hydrogen	1	1	0
Deuterium	1	1	1
Tritium	1	1	2
Helium-4	2	2	2
Carbon-12	6	6	6
Carbon-14	6	6	8

$$m(^{1}H) = 1.008u$$
$$m(n) = 1.009u$$
$$m(^{2}H) = 2.014u$$
$$m(^{4}He) = 4.0026u$$
$$m(^{8}Be) = 8.0055u$$
$$m(^{12}C) = 12.00000u$$

Strong Nuclear Force

- Holds protons and neutrons together in a nucleus
- Strongest force. About 20 times stronger than EM force
- Short range - only extends a little beyond size of proton $(10^{-15}\ m)$
- Mostly attractive but only affects particles like protons and neutrons. Electrons do not "feel" this force

More on Strong Force

As strong force is attractive:

2p + 2n "prefer" being bound together in Helium

"preference" causes mass of He to be smaller than 2p+2n. The mass difference causes energy to be released

What nuclei are stable depends on interplay between attractive strong force and repulsive (between protons) EM force. Some are stable H^1, H^2 C12, and some are not H3, C14 (half lives of 12.3 years and 5730 years)

Weak Nuclear Force

- Affects all particles (except photon)
- Weaker than electromagnetic force except at very high energies where about the same
- Short range - size of proton
- Causes changes in particle type. Many radioactive decays are “weak” and so can occur slowly

proton ↔ neutron

electron ↔ neutrino

particle ↔ antiparticle

Neutrinos - little neutral ones

- Postulated to exist in 1930s, discovered in 1950s.
- Neutrinos (ν) have:

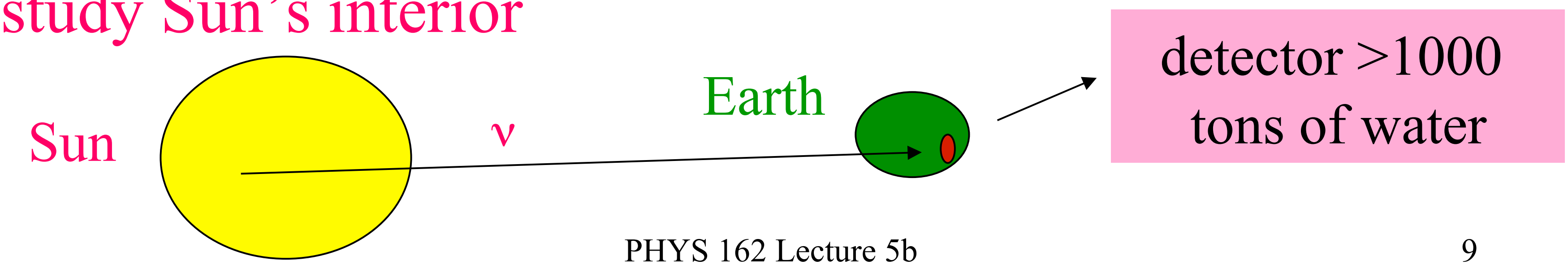
  almost 0 mass

  no electric charge

  unaffected by strong nuclear force

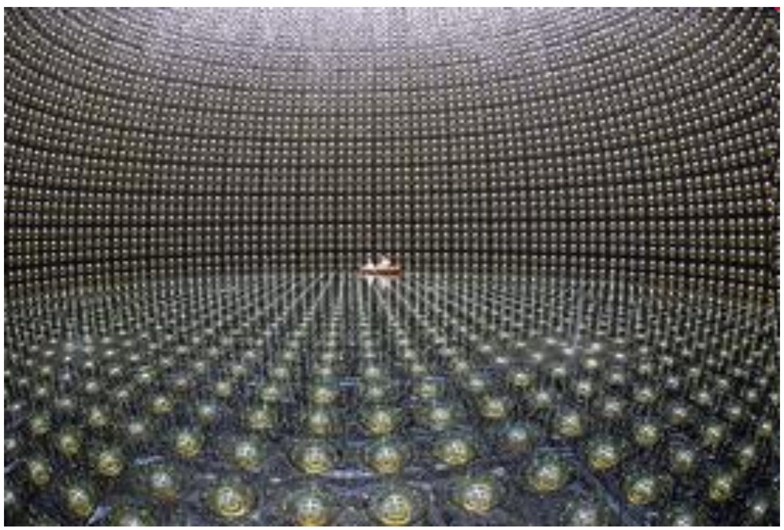
→ and so only interact through the weak nuclear force

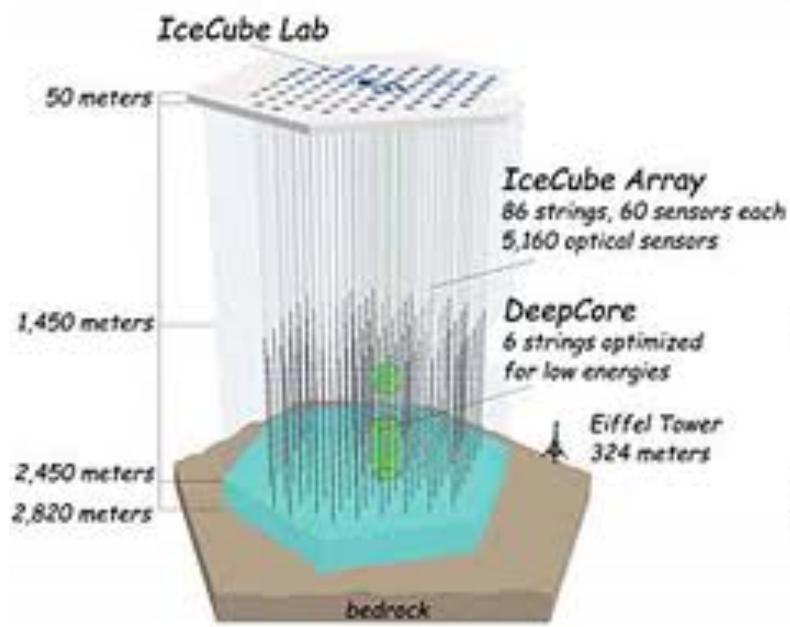
- Only $1/10^{10}$ produced in the Sun's interior interact when going through the Sun's outer layers → so can be used to study Sun's interior



Neutrino Astronomy

- Neutrino observatories can observe neutrinos coming from the Sun, from supernovas, and maybe from black holes
- Most are large water containers deep underground – Japan, Canada, US, Russia, Italy, India (movie 2012)
- Some instrument Antarctica ice or Mediterranean water





Mass converts to Energy

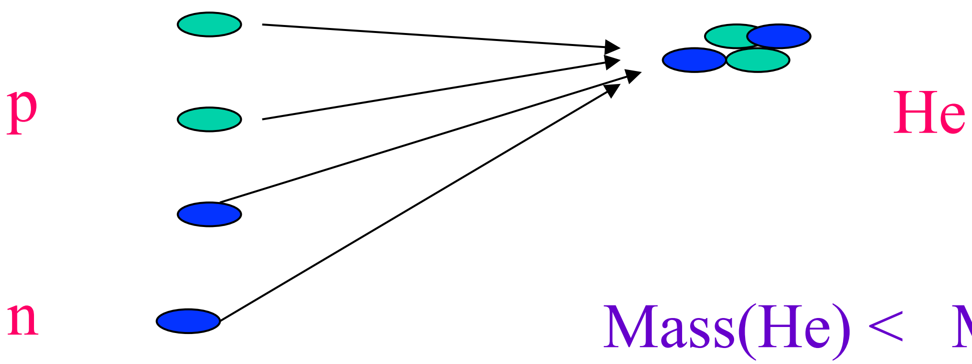
Combining 2 protons + 2 neutrons into Helium converts Mass into Energy/Heat → Source of Sun's energy

$m(^1H) = 1.008u$

$m(n) = 1.009u$

$m(^2H) = 2.014u$

$m(^4He) = 4.0026u$



Mass(He) < Mass(2p)+Mass(2n)

4.0026 < 2.016 + 2.018 = 4.034

Energy difference=binding energy holding n + p together

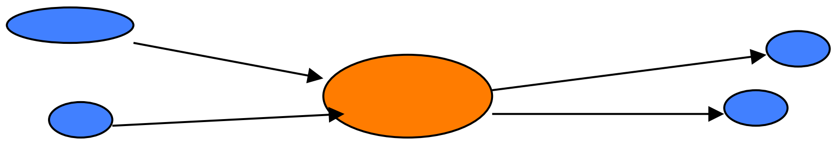
$$E = MC^2$$

Nuclear Reactions

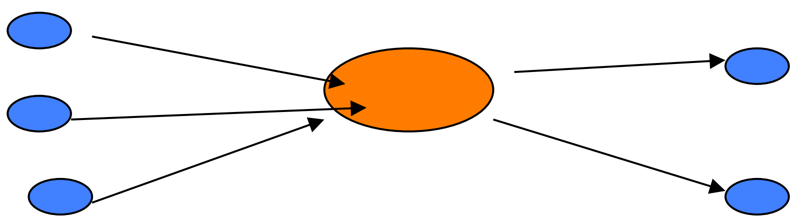
- Nuclear reactions provide the source of the Sun's energy.
- The strong nuclear force binds protons and neutrons together. For example, combining 2 protons and 2 neutrons into Helium converts (by $E=mc^2$) a few percent of the initial particles mass into energy (heat). This is called FUSION.
- For heavier nuclei, the repulsive electromagnetic force between the protons causes them to be less stable.
- Iron is the most stable (largest binding energy per nuclei).
- If heavy nuclei (like Uranium) are broken up into light nuclei, energy is release. This is called FISSION

Nuclear Reactions Primer

- No free neutrons exist (lifetime is 15 minutes)
- The electric force between protons is repulsive. Need high temperatures (at least 5 million degrees K) to get nuclei close enough together for the strong force to bind them together
- usually 2 body reactions, as much more probable

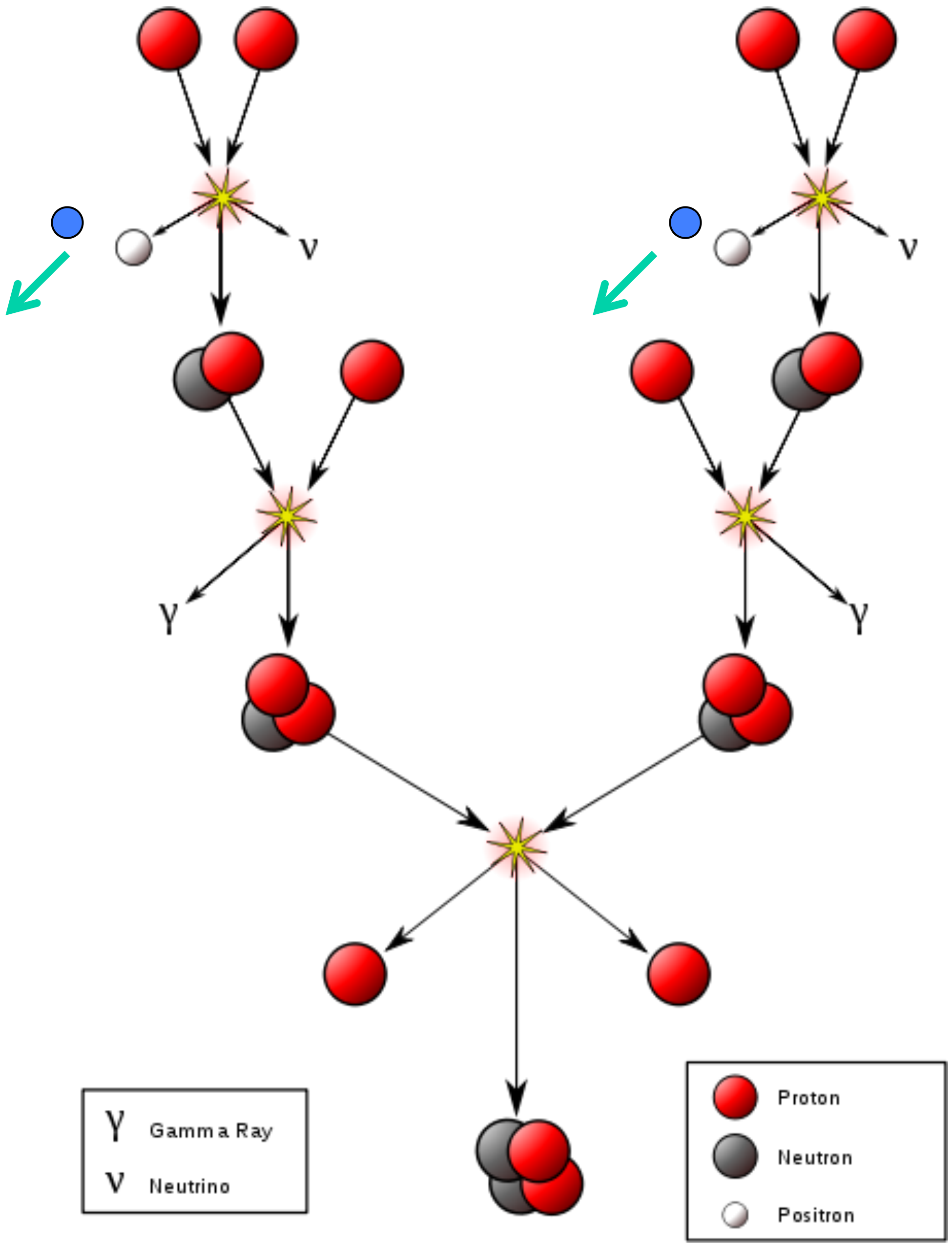


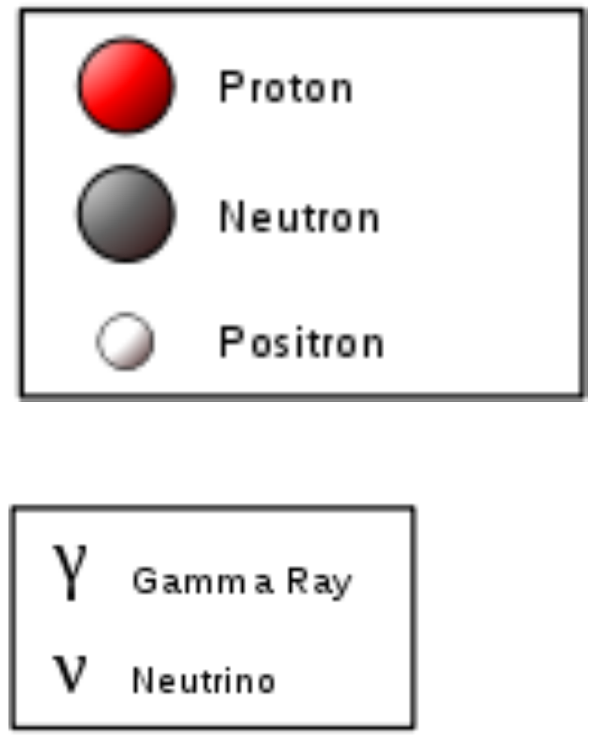
2 to 2



3 to 2

Proton-proton cycle
3 steps





Proton-proton cycle: Reaction 1

$p + p \rightarrow (pn) + e^+ + \nu_e$

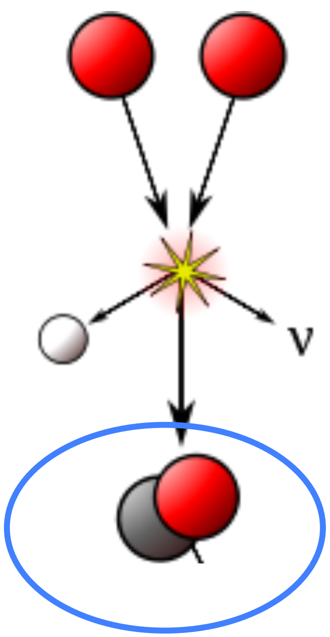
$m({}^1H) = 1.008u$

$m(n) = 1.009u$

$m({}^2H) = 2.014u$

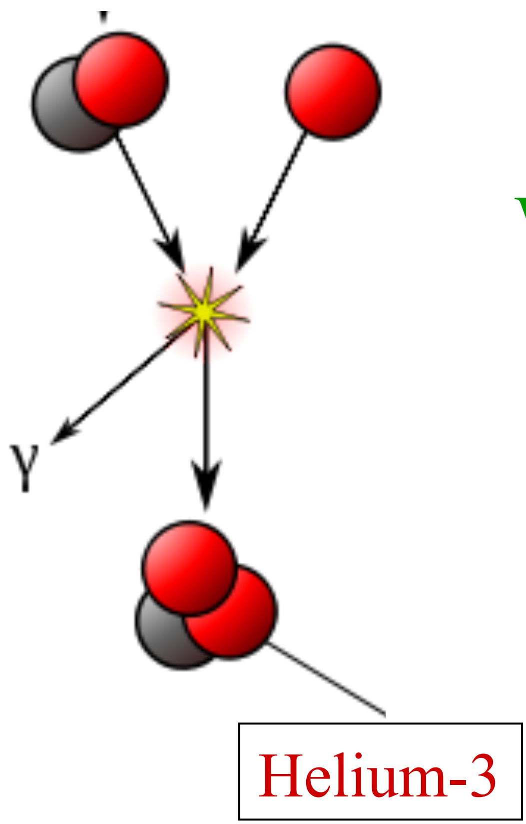
(pn) is a Deuterium nucleus (heavy hydrogen)

- e^+ is a positron. It is the antiparticle of an electron (electrons and positrons can annihilate each other)
- ν_e is a neutrino. Basically an electron without any charge. Only feels **weak nuclear force**
- Reactions releases energy since Mass(D +electron+neutrino) is less than Mass(p+p)
  $2.014 + .0005 + 0 < 2.016$



Deuterium

p-p cycle Reaction 2

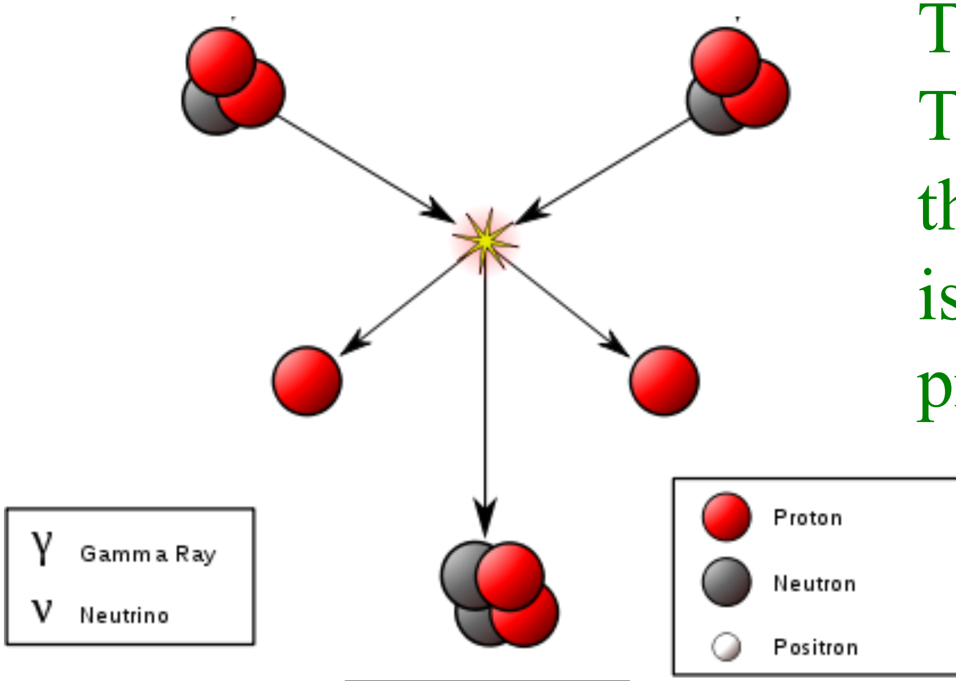


(pn) + p → (ppn) + γ

Where a Deuterium nucleus (pn) absorbs a proton and becomes Helium-3 (ppn). The Helium is in an excited state and emits a photon (γ) as it moves to the ground state

p-p cycle: Reaction 3

(ppn) + {ppn} → (ppnn) + p + p



Helium-4

Two He-3 nuclei collide. They rearrange particles so that a very stable He-4 nuclei is formed with 2 extra protons left over.

Total p-p cycle

- p+p+p+p+p+p → (ppnn) + ν + ν + Energy

  or 6 protons are used to form 1 Helium nucleus plus 2 neutrinos plus Energy (in the form of the 2 positrons and 2 protons)
- Sun is converting Hydrogen into Helium
- Sun is converting part of its Mass into Energy.
- In 10 billion years about 1% of Sun's mass is so converted (and then fusion burning stops)
- Fusion rate depends on temperature and density of the core

Summary

- The STRONG NUCLEAR force can cause energy to be released if protons and neutrons are combined
- High temperatures, provided by the GRAVITATIONAL force, is needed to overcome the ELECTROMAGNETIC repulsive force.
- Neutrons must be made from protons by the WEAK NUCLEAR force.
- All 4 forces are necessary for the Sun to produce energy