Energy Source for Stars

- A really good question is `how do stars produce all that luminous energy'
- The answer should also naturally explain the main-sequence and the mass-luminosity relation.
- Let's start with the Sun. Requirements are:

  (1) $L=4x10^{33}$ ergs/sec

  (2) for ~4.5 billions years

Coal or Wood Burning

- What is `burning'? The conversion of molecular binding energy into heat.

Coal burning efficiency: 4×10^{12} ergs/gram

A 3000gram bucket of coal will generate

1.2×10^{16} ergs = 300 kilowatt-hrs

which would power a little space heater for about an hour.

Coal Burning

- Suppose all 2 x 10^{33} grams of the Sun are coal. The total energy you could generate would be:

$$E_{total} = \left(4 \times 10^{12} \frac{ergs}{gram}\right) \times \left(2 \times 10^{33}\, grams\right) = 8 \times 10^{45}\, ergs$$

- That's a lot of energy! At the rate of L_o, how long would the Sun last?

Coal Burning Lifetime

$$t = \frac{8 \times 10^{45}\, \cancel{ergs}}{4 \times 10^{33}\, \frac{\cancel{ergs}}{\sec}} = 2 \times 10^{12} \sec = 63000\, years$$

- If you were not sure of the right equation, remember dimensional analysis!
- By the mid-1800s it was recognized that the Earth was at least *millions* of years old.
- Note: L_o is equivalent to 1 ton of coal burned per second per square foot of the solar surface.

Gravitational Potential Energy

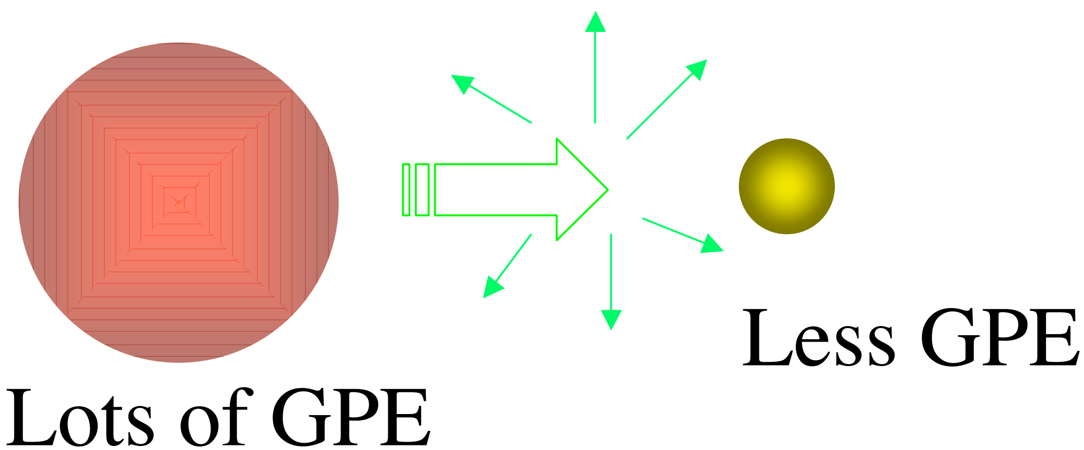
- Anytime you have a collection of mass, there is associated gravitational potential energy (GPE). For a sphere of gas (like a star for example) the GPE is given by:

$$GPE = \square \frac{5}{3} \square G \square \frac{M}{R^2}$$

- Where R is the radius of the sphere, M is the mass and G is the universal gravitational constant.

GPE

- Imagine a large gas cloud that shrank in radius at constant mass.



- Difference in GPE (actually 1/2 of it) must be released as E-M radiation during the shrinking.

GPE

- Note that we are familiar with this idea based on life on Earth. A piano on the edge of a cliff has more GPE than it has at the bottom of the cliff (it is at a larger R from the center of the Earth).
- Drop the piano and this GPE is converted into kinetic energy, then into sound waves, breaking molecular bonds and heat.

GPE efficiency

- We can calculate the GPE of the Sun from the formula a few slides back:

$$GPE_{Sun} = 2 \times 10^{48} \, ergs$$

- If we could extract this amount of energy for radiation (by letting the Sun shrink) it would yield:

$$Eff(gpe) = \frac{2 \times 10^{48} \, ergs}{2 \times 10^{33} \, grams} = 10^{15} \frac{ergs}{gram}$$

GPE

- This is 250 times more efficient than chemical burning, but if you do the lifetime calculation again:

$$t = \frac{2 \times 10^{48} ergs}{4 \times 10^{33} ergs/\sec} = 5 \times 10^{14} \sec = 16 \times 10^{6} years$$

- Still too short! (Plus the Sun would have to have been much larger in the past)

GPE

- A variant of this method was considered a serious possibility until the early 1900s. Comets falling into the Sun would make a good energy source. Only need about 1 Earth mass per year . The mass of the Sun would be increasing, and there is no evidence from changes in the Earth's orbit to support this idea.

Nuclear Power

- The answer for the power source of the Sun had to await the discovery of the nucleus and the nuclear force.

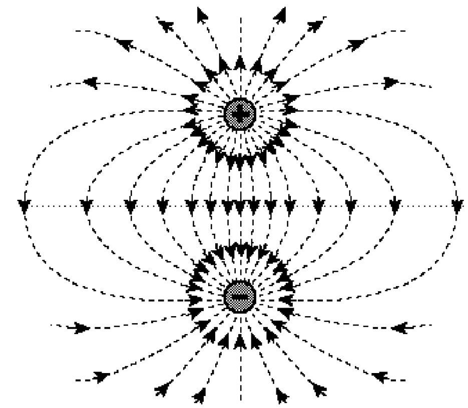
Forces of Nature

- First, let's review the fundamental forces.

(1) Gravity is an attractive force between objects with mass. This keeps you in your seat, keeps the Earth in orbit around the Sun, prevents the hot gases in the Sun from expanding away into space and other useful stuff.

This is the weakest of the fundamental forces.

Forces of Nature



(2) Electric Force between electrically-charged objects (protons and electrons).

Like charges Repel, opposite charges Attract. This is the force that holds atoms and molecules together and is useful for running nifty gadgets. It is also the reason that you don't fall through the floor and get cooked in the middle of the Earth.

Chemical burning is converting electrical forces into E-M radiation.

Forces of Nature

(3) Weak Nuclear Force. This is responsible for radioactive decay of some nuclei.

(4) Strong Nuclear Force. This is an attractive force between nucleons and it is what binds protons and neutrons together in the nuclei of atoms

Which force is stronger, electric or nuclear strong force?

Must be the nuclear strong force! The protons in a nucleus repel one another, yet nuclei are not flying apart. In fact, the Nuclear strong force would right this minute be binding everything in the Universe into a tiny ball except for the fact that is only acts over VERY TINY distances.

The Four Forces

- Note that Gravity is MUCH weaker than the electric force or the strong nuclear force. Comparing the electric repulsion of two protons to their gravitational attraction, gravity is weaker by a factor of 10^{36}.
- So, why is gravity the force we see dominating the Universe?

Energy from the Nuclear Force

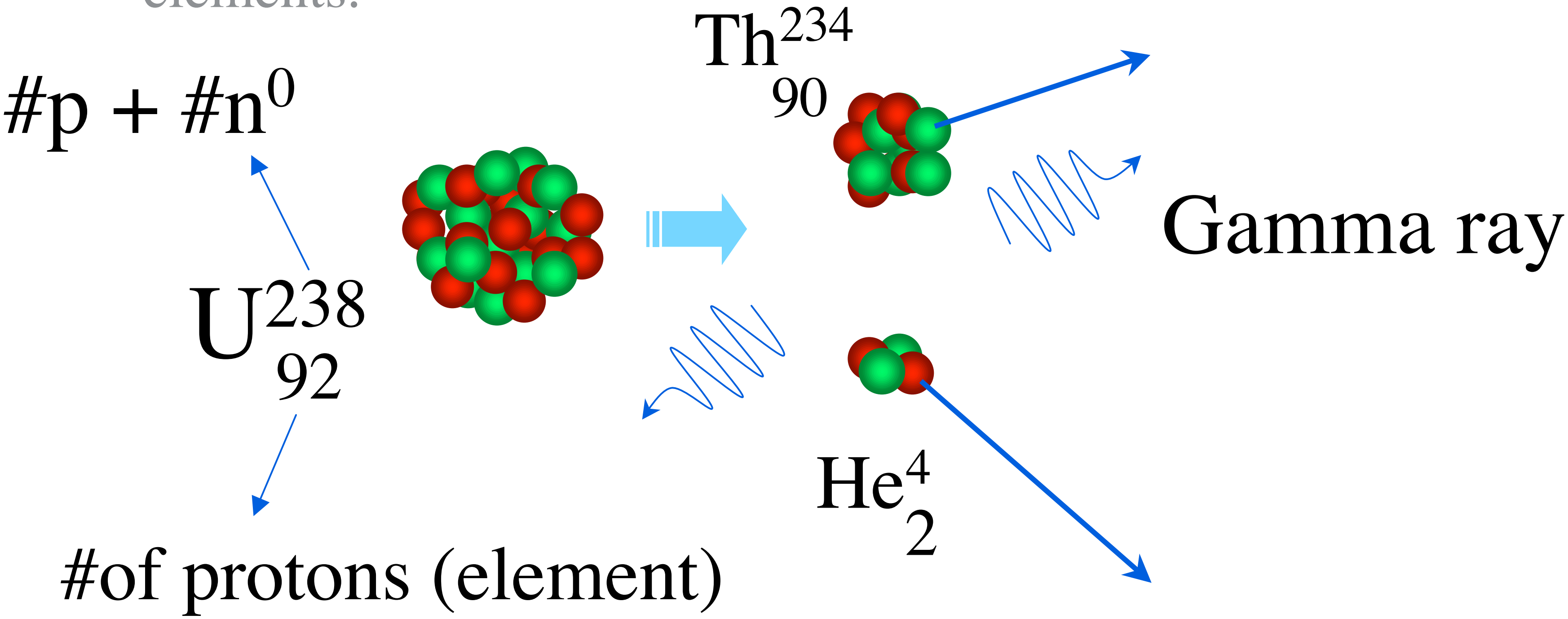
- There are two paths to deriving energy from nuclear reactions (a nuclear reaction is adding or subtracting a proton or neutron from a nucleus).

(1) Nuclear Fission

(2) Nuclear Fusion

Nuclear Fission

- There are some elements in the Periodic Table that spontaneously fall apart. These are the radioactive elements.



Nuclear Fission

$U^{238} \Rightarrow Th^{234} + He^{4}$

There is a remarkable thing!

$Mass(U^{238}) > Mass(Th^{234}+He^{4})$

Mass Defect

- Even though there are the same number of nucleons before and after, a little mass disappeared in the reaction. This mass is associated with the difference in Nuclear Binding energy before and after.
- The missing mass has been converted into energy via everyone's favorite physics equation!

$$E = mc^2$$

In this application, `m' is the mass that went missing and `E' is the energy released in the form of gamma rays. For some fission reactions, the amount of energy released per gram of missing mass is large.

Nuclear Fission

Fission can release as much as

10^{18} ergs/gram

Recall, coal burning released

4×10^{12} ergs/gram

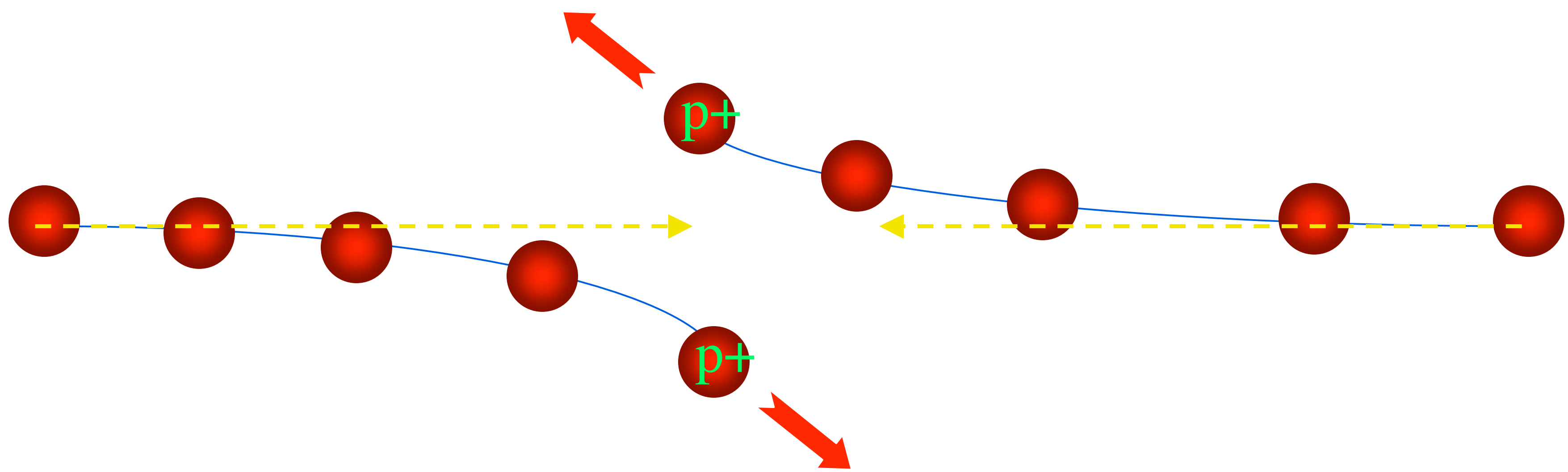
- Nuclear fission could produce enough energy to fuel the Sun for ~6×10^{10} years IF the Sun were composed completely of fissionable material.
- It is not! For example, the Uranium abundance in the Sun is less than a millionth of the solar mass.

Nuclear *Fusion*

- Imagine a gas of protons (p+). At `low' temperatures the electrical repulsion force prevents the close approach of two p+
- But as T increases, the minimum approach distance decreases and some p+ get close enough (10^{-15}m) for the short-range, but VERY STRONG nuclear force to bind them together.

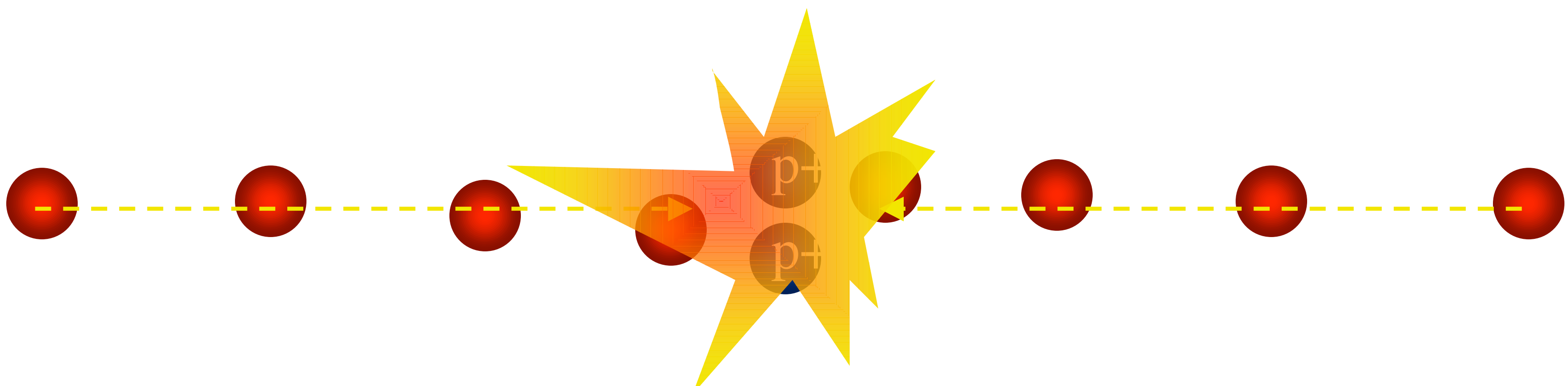
Hydrogen (proton) fusion

Like electrical charges repel. So, protons in a gas *avoid* `collisions’



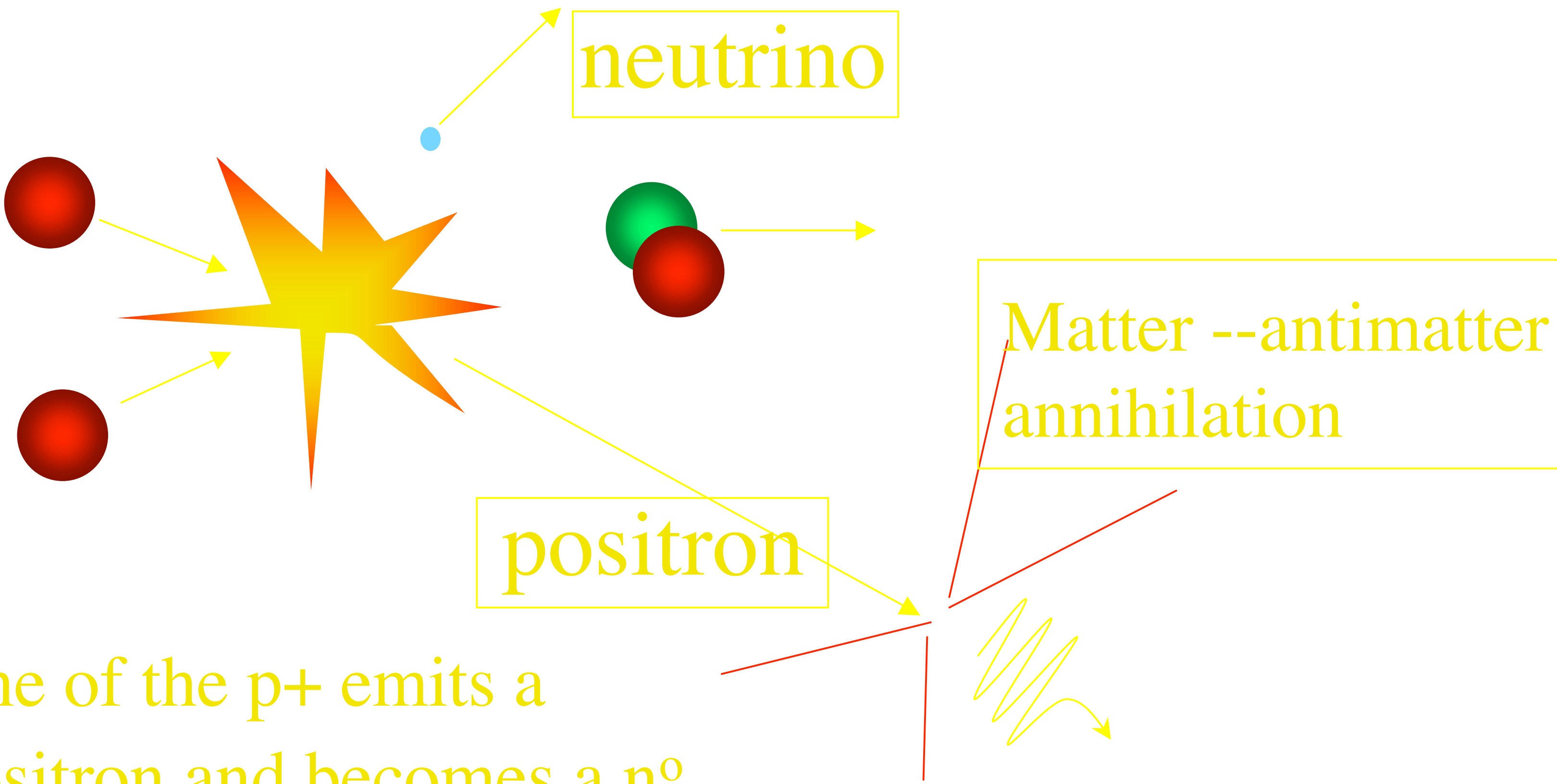
Hydrogen (proton) fusion

However, as a gas temperature goes up, the average speed of the particles goes up and the protons get closer before repelling one another. If the proton get very close, the short-range *nuclear force* fuses them together.



Hydrogen Fusion

- Proton fusion involves some interesting ideas.



One of the p+ emits a <u>Positron</u> and becomes a n°

Hydrogen Fusion

When two protons fuse, almost immediately one turns into a neutron by emitting a positively charged electron (known as a positron and `beta-decay'). The e+ is antimatter (!) When it comes into contact with its matter partner (e-) it annihilates entirely into energy.

What element has a nucleus with 1 proton and 1 neutron? Deuterium (heavy hydrogen)

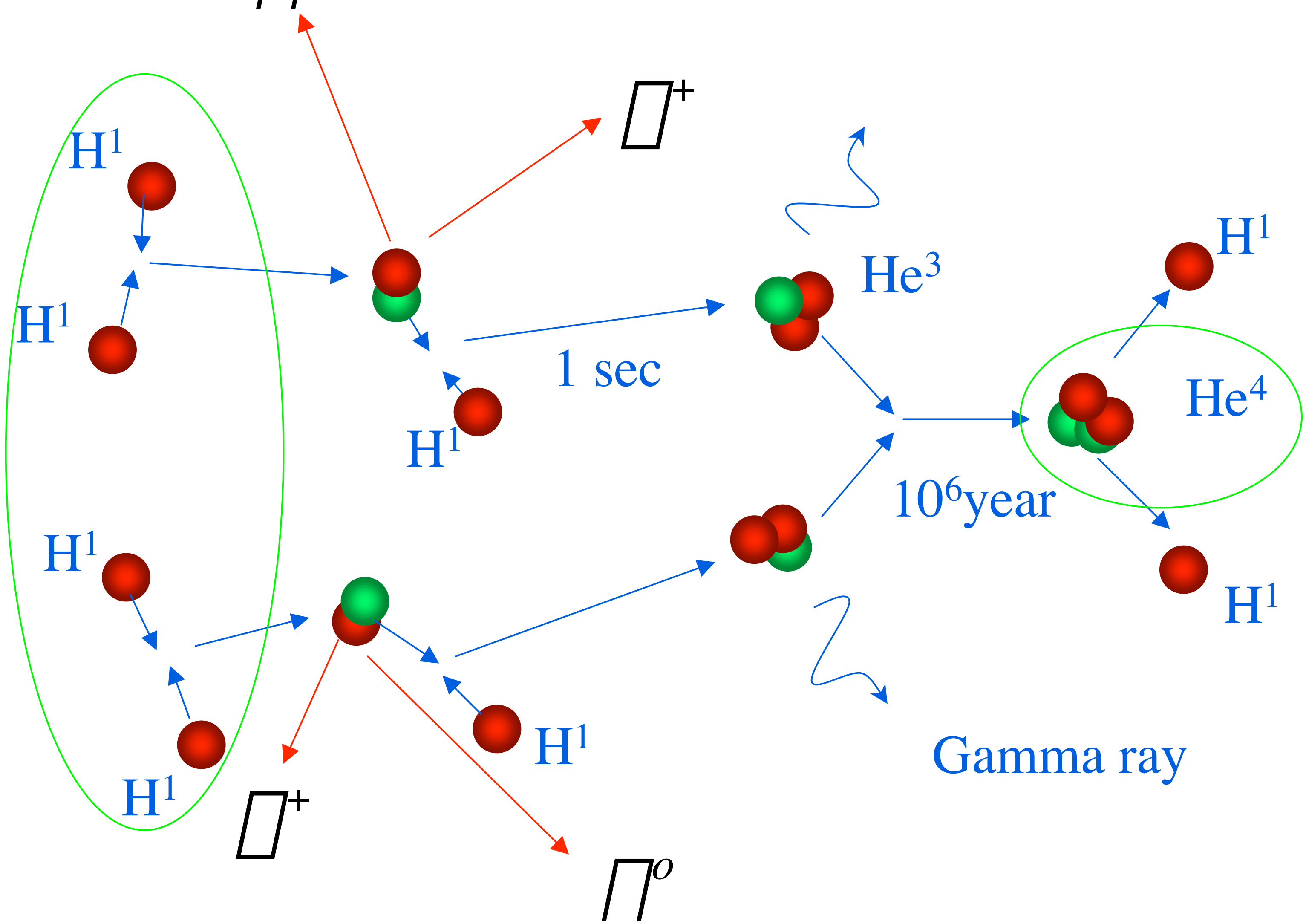
Neutrinos

- Another curious particle that flies out of the reaction is called a `neutrino' (little neutron).
- This is a chargeless, perhaps massless particle which has a tiny crossection for interaction with other types of matter. The mean free path in lead is five light years.
- Neutrinos were first postulated in 1932 to account for missing angular momentum and energy in beta-decay reactions (when a proton becomes a neutron and emits a positron).
- Neutrinos are leptons - subatomic particles that participate in weak interactions, but not the strong nuclear force.

Neutrinos

- The Sun emits about 10^{38} neutrinos/sec.
- Humans emit about $3x10^{8}$ neutrinos/day (radioactive potassium).
- Every second we have many neutrinos pass through our bodies: 400,000 billion from the Sun, 50 billion from the Earth and 100 billion from nuclear power plants.

P-P Chain



P-P Chain

- The net result is

$$4H^1 \rightarrow He^4 + \text{energy} + 2\ \text{neutrinos}$$

where the released energy is in the form of gamma rays.

The source of the energy is again a tiny bit of mass that goes missing:

Mass(4H) = 6.6943×10^{-24} grams

Mass(He^4) = 6.6466×10^{-24} grams

P-P Chain

- The amount of missing mass is:

$$\Delta mass = 0.048 \times 10^{-24}\ grams$$

- The energy generated is:

$$E = \Delta mc^2 = 4.3 \times 10^{-5}\ ergs$$

- This much energy is released by $4H^1$ with a total mass of 6.6943×10^{-24}grams. The efficiency of hydrogen fusion is therefore:

6.4×10^{18} ergs/gram

Sun's Lifetime with H-fusion

- Total energy available:

$$6.4 \times 10^{18}\,\frac{ergs}{gram} \times \left(2 \times 10^{33}\,grams\right) = 12.8 \times 10^{51}\,ergs$$

- Lifetime of the fusion-powered Sun

$$\frac{12.8 \times 10^{51}\,ergs}{4 \times 10^{33}\,\frac{ergs}{\sec}} = 3.2 \times 10^{18}\,\sec = 10^{11}\,years$$

100 billion years

- This is promising! Is hydrogen fusion for real? Yes, remember Bikini Atoll.

Requirements for a Fusion-powered Sun

(1) Need lots of protons (H nuclei). ☑

Element	Abundance (#)
Hydrogen	92.0%
Helium	8.3%
Oxygen	0.06%
Carbon	0.02%
Nitrogen	0.01%
The rest	…

Requirements for Fusion-powered Sun

(2) **Need a high temperature**. For the p-p chain the gas temperature needs to be $>10^7$K.

- Recall the discussion about stellar structure. In the center of the Sun, hydrostatic equilibrium requires the temperature to be around 15 million K. In the center 10% of the Sun $T > 10^7$K

Fusion-powered Sun

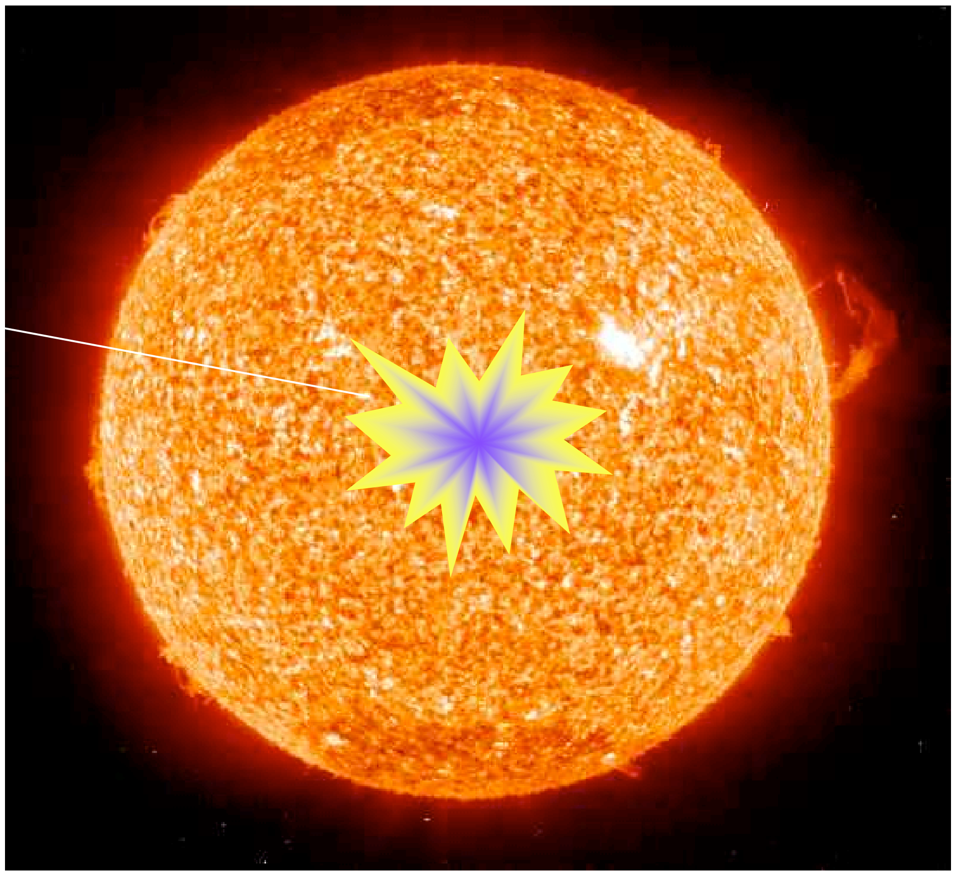
1) Lots of fuel

2) Conditions are right in the central 10% for the P-P cycle to run

3) P-P fusion is efficient enough to power the Sun for billions of years.

Looks like the Answer!

H -->He

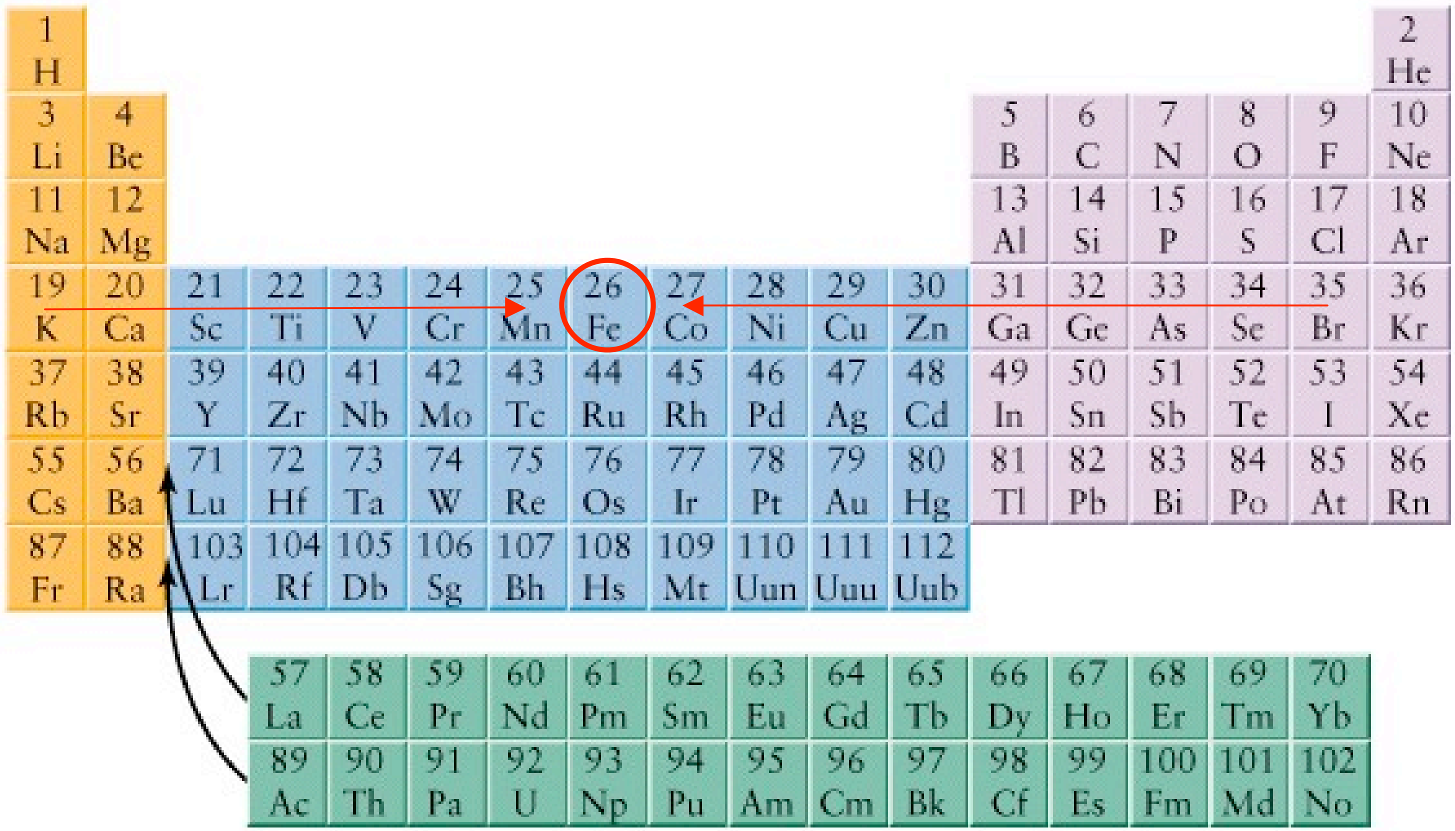


Note a small falsehood

- In the Sun, the protons don't really get close enough for the nuclear force to be stronger than the electric repulsive force.
- Fusion in the Sun (and life on Earth) is the result of a very odd property of atomic matter called Quantum Tunneling.
- An analogy is me running full speed and attempting to leap over a 30-foot-tall wall. Most attempts, I crash into the wall and fall to the ground. But, once in awhile, even though I don't leap 30' into the air, I am successful and end up on the other side of the wall.

Fusion vs Fission

- We'll talk about this in more detail later, but the way nuclei are put together, you get energy released when *fusing* light elements and when heavy elements *fission*. The breakpoint is iron.



1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Uun 111 Uuu 112 Uub
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No

Fusion-powered Sun

- An interesting aside. To produce the solar luminosity, the Sun is converting matter into energy:

$$4 \times 10^{33} \frac{ergs}{\sec} \times \frac{1}{6.4 \times 10^{18} \frac{ergs}{gram}} = 6.25 \times 10^{14} \frac{grams}{\sec}$$

- This is the amount of H --> He per second. The amount of matter converted to energy is:

<u>4.3 million tons per second</u>