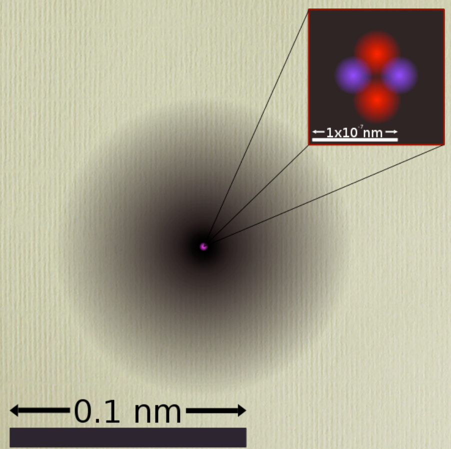
Nuclei

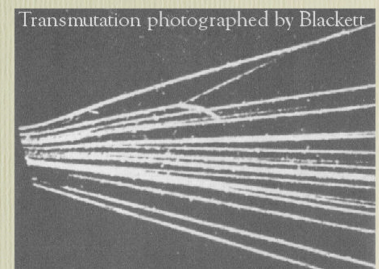


Peter Watson

Helium

The Proton

- Discovered as nucleus of H by Rutherford and Blackett (1921) in
- $\alpha + N \rightarrow O + p$
- $q_{proton} = +1\times1.6\times10^{-19}$
- $m_{proton} = 1.67\times10^{-27}$ kg



Blackett

Neutron

- discovered by Chadwick (1932) as penetrating **massive** neutral particle (i.e., not a γ)
- $q_{neutron} = 0$
- $m_{neutron} = 1.68\times10^{-27}$ kg
- since neutrons and protons are so similar in mass, convenient to think of them as the same particle (a nucleon) which comes in two flavours!

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Nuclei

- Atomic Number Z = charge on nucleus= $N_{protons}$
- This defines chemistry
- Mass number $A = N_{protons} + N_{neutrons}$
- Isotopes: nuclei with different A but same Z.

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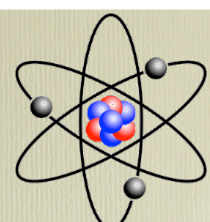
Notation



- We need to have some way to describe the nucleus we are talking about
- Lithium nucleus has 3 protons and 4 neutrons so

$${}^{7}_{3}Li_{4}$$

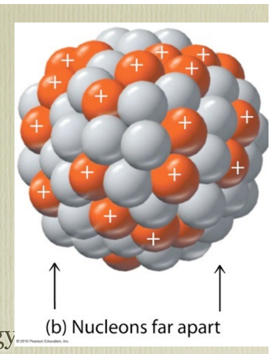
However you can always figure out the $N_{neutron}$ so $${}^{7}_{3}Li$$

Name implies Z, so simply $${}^{7}Li$$

Wikisource

The sizes of things:

- a proton is about 1 fm $=10^{-15}$m in radius.
- A nucleus is a close-packed array of protons and neutrons, so radius
- $R \sim 1.4\, A^{1/3}$
- Just as electrons in atoms have energy levels, so do nucleons
- Typical energy levels in nuclei tend to be separated by 10 MeV (million), compared to 10 eV in atoms.



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Conservation Laws

- A lot of what happens inside atoms is governed by conservation laws
- e.g. charge must be the same at start and end, so

$n \Rightarrow p\gamma$

- cannot happen ($0 \neq 1+0$!)

- Neutrons and protons can turn into each other but can't disappear

$n \Rightarrow \gamma + \gamma$

- doesn't happen
- $N_{proton} + N_{neutron}$ stays the same

Most important

- Conservation of energy
- Need to extend our definition of energy to include mass-energy

$$E=mc^2$$

If a reaction is allowed and changes the mass of the nuclei, then energy is released

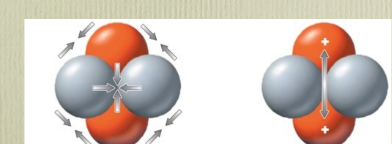
- e.g. 1 kg of matter converted to energy gives
- $E = 1\times(3\times10^8)^2 \sim 10^{17}$ J

Forces

Forces	"Feels"	Range	Strength
Gravitational	Mass	∞	10^{-41}
Weak	Matter	10^{-18} m	10^{-7}
Electromagnetic	Charges	∞	1/ 137
Strong	Baryons	10^{-15} m	10

- Note: "feels" means that this is what the force couples to: e.g. gravity does not care whether a particle is charged, only whether it has mass.
- Range: if it is ∞ then $F \sim 1/r^2$, else it cuts off at distance shown
- Strength: roughly the relative strength of the forces at a distance of 1 fm.

- Strong force >>> E.M at 1 fm ($=10^{-15}$ m), but vanishes totally beyond 10^{-14} m.
- E.M >>> Gravity, but it tends to cancel out since most matter is electrically neutral, whereas mass accumulates.
- Strong force governs behaviour of nuclei
- All nucleons attract each other by strong (short-range) force
- Protons repel at long distances



All nucleons, both protons and neutrons, attract one another by the strong nuclear force.

Only protons repel one another by the electric force.

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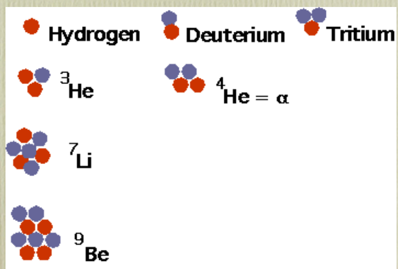
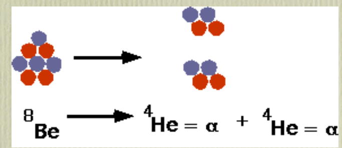
What governs what nuclei exist?

- Light nuclei can fuse together
- attractive forces win out

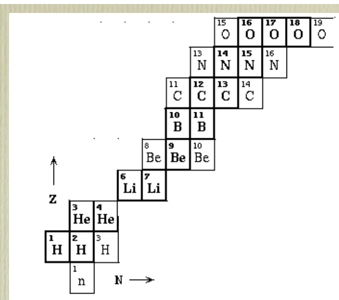


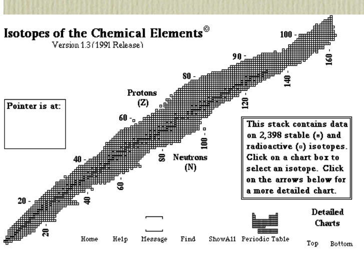
- Note that there are no stable elements of A = 5 or A = 8:
- if you make ^{8}Be it will decay instantly into 2 ^{4}He.



- Roughly speaking, need equal numbers of p and n: if a nucleus is badly out of balance, it will undergo a decay.

- Many nuclei can be created but only a few are stable:
- this shows nuclei up to oxygen.



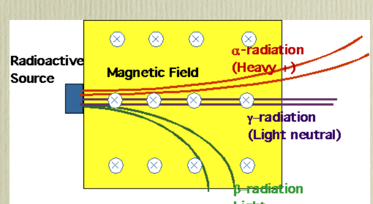


- Whole pattern shows N ~ Z for light, N > Z for heavy.

- Lightest nucleus is H
- Heaviest stable nucleus is lead ^{208}Pb
- Naturally occurring nuclei exist up to uranium ^{238}U

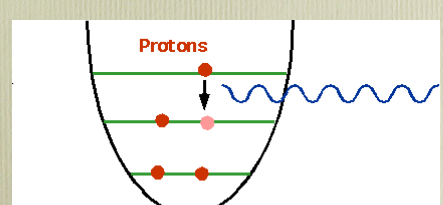
Radioactivity and Decays Becquerel (1896)

- (alpha) α-rays ~heavy, positively charged
- (beta) β-rays ~ light, negatively charged
- (gamma) γ-rays ~ neutral, light



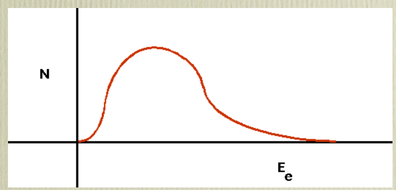
Simplest conceptually is γ-decay

- just as atoms have energy levels, so do nuclei. .
- One of the protons (or neutrons) can make a transition if there is a vacancy.Energy is much higher than in atoms: ~ 10 MeV.

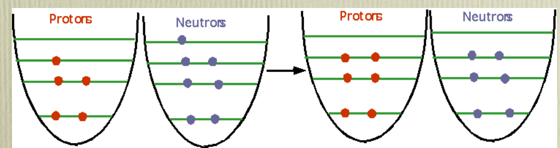


β-decays

- β particle is just an electron
- an isolated neutron will decay.
- $n \rightarrow p + e^-$
- This led to a huge problem: the electron came out with varying energy.

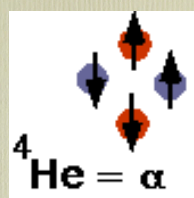


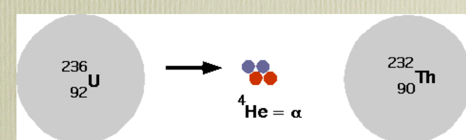
- Fermi (1933) proposed that the missing energy is carried off by an invisible particle, the neutrino (symbol is nu: ν) , so the real reaction is:
- $n \rightarrow p + e^- + \nu$
- This can also happen in a nucleus if the energies are favorable: e.g. could have



α-decays

- Occurs in heavy nuclei. He nucleus is very tightly bound, since it has 2 protons, 2 neutrons
- Heavy nuclei are unstable, since they have repulsive forces between the protons. Hence





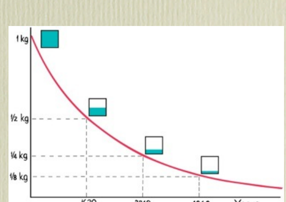
Radioactive Decays

- All radioactive decays have a similar behaviour.
- The decay occurs totally at random
- probability of decay is proportional to the number of nuclei:
- This reduces the number of nuclei available to decay
- Half-life: time taken for half the nuclei to decay.

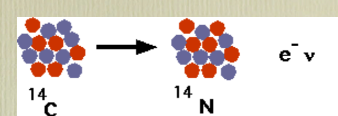
- Half-life: time taken for half the nuclei to decay
- e.g. ^{13}N has half-life of 10 minutes

  $^{13}N \rightarrow {}^{13}C + e^+ + \nu$

- If we start with 1000 nuclei, how much would be left after 30 minutes?
- after 10 minutes ~500 atoms
- after 20 minutes ~250 atoms
- after 30 minutes ~125 atoms



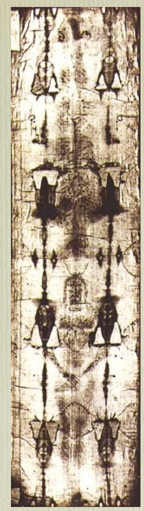
Carbon dating



- In the atmosphere, some of the $^{14}N \rightarrow {}^{14}C$ by cosmic rays.
- This gets incorporated in living things, substituting for ^{12}C
- When the object dies, no more ^{14}C is absorbed,
- What is already there decays back to ^{14}N, with a half-life of 5700 years.

Turin Shroud

- (supposedly used to wrap Christ in when he was lowered from the Cross)
- Proportion of ^{14}C which is 89.5% of that of current materials.
- ➠ age of about 800 yrs



WIkipedia

Nuclear Energy

- Most chemical reactions (e.g. burning of gasoline) give out ~ 100 MJ/kg.
- At the atomic level, this implies about 10 electron-volts/atom: e.g.
- $C + O_2 \rightarrow CO_2 + \sim 5eV$
- an atom in a gas has an energy of about 1/40 eV

Fission Reactors

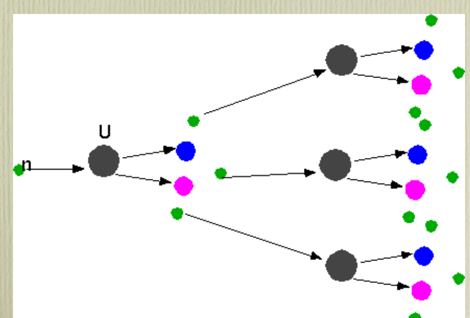
- A typical fission reaction: this would provide about 100 MeV of energy per fission.

$$^{235}_{92}U \Rightarrow {}^{129}_{53}I + {}^{106}_{39}Y$$

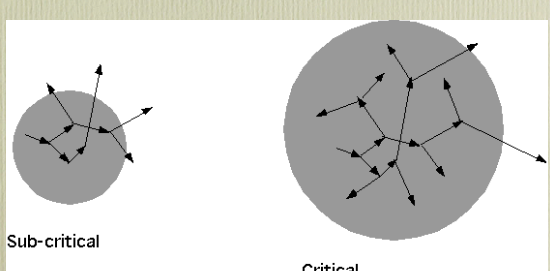
- Note Z & A are conserved
- However, only some nuclei will fission easily:
- ^{235}U will undergo a fission reaction with slow neutrons

$$^{235}_{92}U + n \Rightarrow {}^{142}La + {}^{90}Br + 4n$$

- No control over breakup process, usually fissions into one lighter and one heavier nucleus and extra neutrons
- Release of n's allow chain reaction



- However, some of the neutrons can leak out before they can cause another reaction.
- Hence need enough fissile material so that average n does not escape...
- Critical mass for ^{235}U is ~ 2.5 kg.

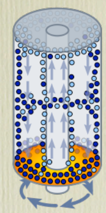


Catches:

1. How do we get fissile material?
2. How do we assemble enough material to reach a critical mass?
3. How do we slow down the neutrons?
4. How do we control a reaction once it has gone critical?
5. How do we get the energy out?
6. How do we handle radioactive wastes?

How do we get fissile material?

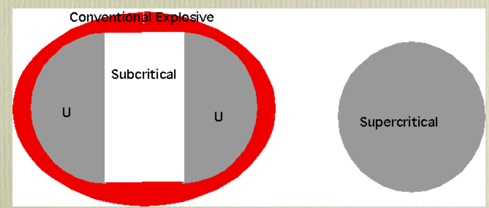
- Natural uranium is ~ 99.3% ^{238}U, .7% ^{235}U
- ^{238}U doesn't fission easily so need enriched uranium
- ^{235}U is lighter than ^{238}U, so form gas (uranium hexafluoride)
- use heated centrifuge to enrich with ^{235}U
- CANDU uses natural uranium, most reactors need ~ 5% ^{235}U



Wikipedia

How do we assemble enough material to reach a critical mass?

- In bomb, start off with 2 subcritical lumps, "assemble" them to make supercritical lump by imploding with conventional explosives.



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How do we slow down the neutrons?

- Need moderator: a light nucleus, so that elastic collisions will remove energy from n's: e.g. Beryllium

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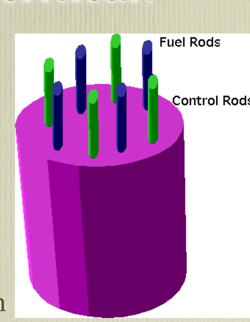
How do we control a reaction once it has gone critical?

- Fuel: usually natural U enriched with ^{235}U
- Moderator to slow down neutrons:
- Absorber: to allow process to be controlled by absorbing neutrons. usually cadmium
- Moving rods in and out allow reaction to be controlled. About 1% of neutrons are delayed by up to 1 min.



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How do we get the energy out?

- Usually steam is passed though reactor core
- Core remains hot even after reactor has been turned off ......

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How do we handle radioactive wastes?

- e.g. ^{90}Br ➠ ^{90}Sr very quickly
- This is long-lived, gets incorporated into bones (chemically similar to Ca), and can decay there, damaging the bone-marrow.
- Similarly ^{131}I damages thyroid.
- Keep high level wastes above ground until most active components have decayed, then encapsulate in glass and bury.
- Long-lived wastes have $t_{1/2}$ ~ 1000 to 10^8 yrs.

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What went wrong?

1. at Chernobyl
2. at Fukushima

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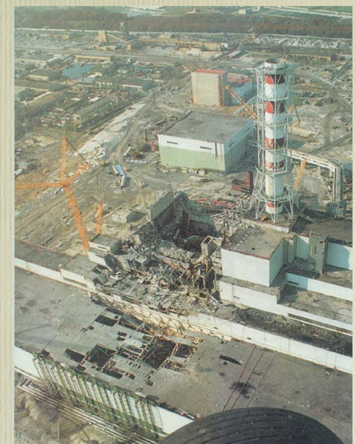
Chernobyl

- unauthorised experiment to test emergency emergency cooling system for 3000MW system
- pumped in water, absorbing neutrons 200 MW
- removed control rods
- water boiled, reactor power started increasing
- control rods stuck
- Power surges to 30GW, core catches fire and explodes
- ~ 30 immediate deaths



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Fukushima

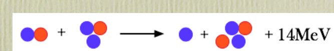
- Emergency pumps flooded by tsunami
- Cores started to melt down
- flooded with sea water, explosion
- secondary containment vessel worked
- Large release of low-level radioactivity

Digital globe satellite

- No deaths from radioactivity,
- ~ 25000 from tsunami

Nuclear Fusion

- Nuclear reactions give out millions of eV/ nucleus: e.g
- Deuterium + Tritium →neutron +Helium



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- e.g. consider D + D ➟ ^{4}He
- Energy involved:
- mass of deuterium (a proton + a neutron) = M_d= 2.014103 u (u = 1.66×10^{-27} kg)
- mass of ^{4}He (2 p, 2 n) M_{He} = 4.002603u
- so can make ^{4}He from 2 D, with some mass left over.
- In terms of energy,
- $E = mc^2 = 0.0254\times1.66\times10^{-27}\times(3\times10^8)^2$ = 23 MeV
- Means 9.5×10^{14}J /kg

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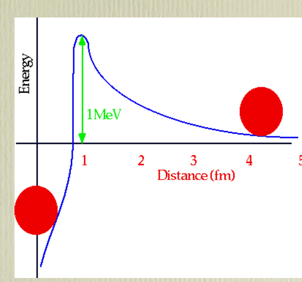
Problem

- there is a very large repulsive force between nuclei, until distances become very small
- ~ 10^{-15} m or 1 femtometre, 1 fm
- Fusion won't happen until we can get over the barrier



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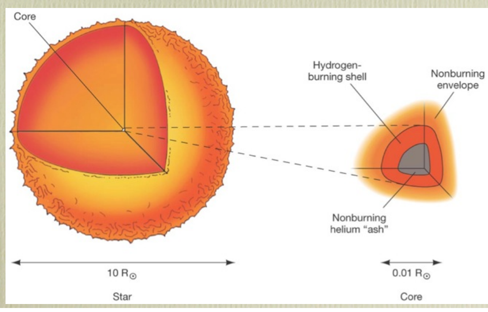
Ways Out:

- Stars: use lots of pressure
- → high temp 15 million °C
- Average energy of protons ~ 100 KeV, so some will fuse.



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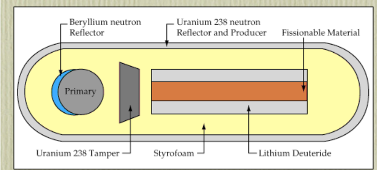
- Hydrogen bomb: heat small amount of gas up to ~10 billion °C for a very short time, by imploding layer.



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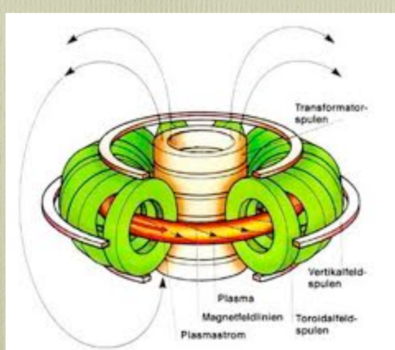
- Magnetic bottle or Tokomak
- confines very hot gas with magnetic fields, for long enough.



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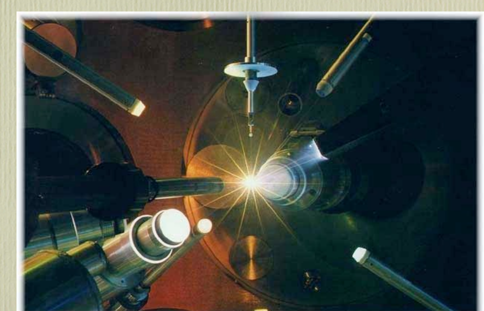
- Laser implosion:
- essentially bomb with lasers used to replace explosive.



The OMEGA 60 Target Area

- None of the methods work satisfactorily

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So how does the sun work?

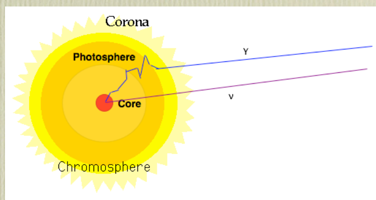
- Sun is ~ 90% hydrogen,
- ~9% Helium
- ~1% everything else
- It "burns" H to He (almost the same reaction as a hydrogen bomb!)

PW

- Every second the sun converts 4 million tons of matter into energy!

er Watson

- And this is what keeps us warm!
- How do we know it's true?
- What really goes on in the core is a bit more complicated
- 4 protons become helium + 2 anti-electrons + 2 neutrinos
- $4p \rightarrow {}^4He + 2e^+ + 2\nu$



The neutrinos produced at the centre make it to earth in 8 minutes

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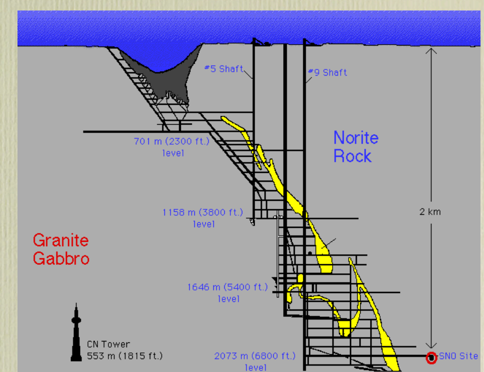
- One Trillion (roughly) go through your thumb each second
- you hadn't noticed?
- tsk tsk!
- If we could see the neutrinos, we can see the centre of the sun!
- but they have almost no interactions

Wikisource

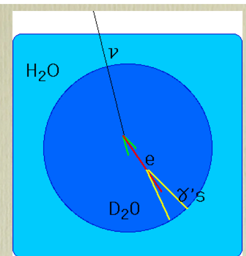
Sudbury Neutrino Observatory

- Let's look at the sun through 2 kilometres of rock!!
- And use 1000 tons of heavy water as our detector



SNO

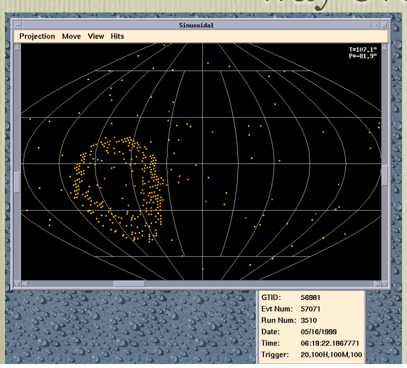
- Once every 3 hours a neutrino will hit an atom and produce light



- Which we can detect

SNO

So neutrinos really come from the core of the sun, but they change into another kind on the way over



Why?
We don't really know, but it means that neutrinos make up more of mass in universe than all the "normal" matter

SNO

- So we understand (more-or-less) how the sun works:
- It is 4.5 billion years old
- "Best before" date is 10 billion years when it runs out of hydrogen fuel

PW