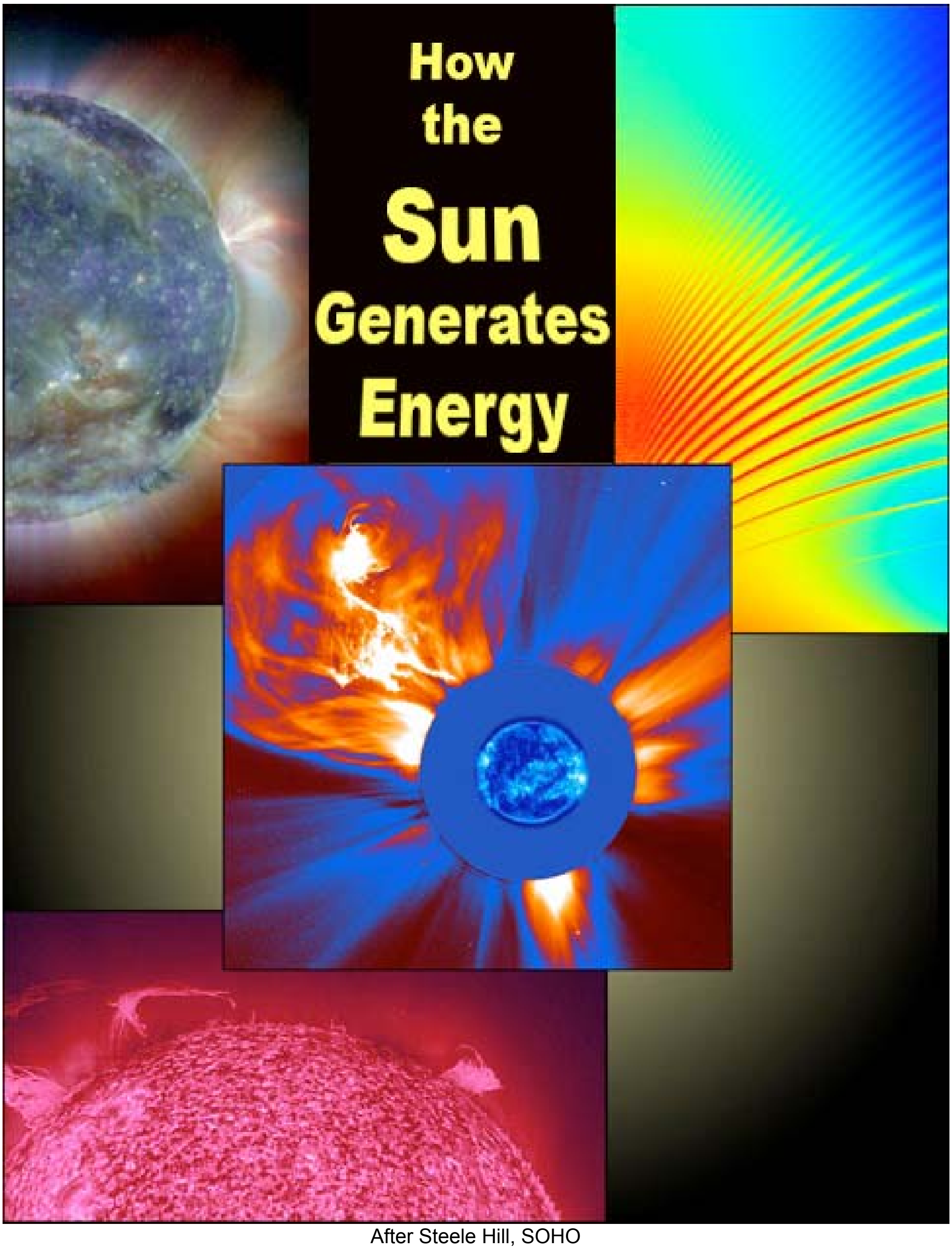
Solar Fusion



After Steele Hill, SOHO

by Michael Gallagher
for the BDAS Astronomy Course
28th April 2006

Sources

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Web Sites

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http://sohowww.nascom.nasa.gov/

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University Corporation for Atmospheric Research UCAR
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http://solar-center.stanford.edu/

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Introduction

For most of human history, people have taken the Sun to be an inexhaustible source of heat and light. That fact that it must be consuming energy to produce its radiant output was, for a long time, unthinkable

The principle of conservation of energy emerged during the industrial age. *Energy cannot be created or destroyed. It can only be transformed from one form to another*. The question of how the Sun produced heat and light then became a serious enquiry for which rational answers were sought.

By the early 1800s, geologists had established that plants and animals had been living on Earth for millions of years. This led to the realization that the Sun's fire could not be ordinary. Its rate of energy production was known. If the Sun were burning combustible material in air, its fuel supply would be exhausted in a few thousand years.

Other explanations were sought. Contraction of the Sun's matter by gravity releases heat and light. The Sun's mass was sufficient for that mechanism to generate heat and light for around a hundred million years.

But geologists and palaeontologists were uncovering evidence that indicated the Earth was billions of years old. The nature of the process that enabled the Sun to shine for such an extraordinary length of time was major unsolved problem at the turn of the 20^{th} century.

The solution lay in an understanding of the incredible energies bound up in the nuclei of atoms*. To understand how the Sun works, we must first understand a little about atoms.

*In the forty years between 1895 and 1935, atomic physicists made an astounding series of discoveries that set the stage for the modern world. Matter and energy were found to be related. Nuclear fission and fusion were discovered and understood. Tools for probing atoms and nuclei were sought – cathode ray tubes, X-ray generators, mass spectrometers and particle accelerators were developed. Medical X-ray machines, fluorescent lights, radio valves and television tubes were among the spin-offs that ushered in the electronics age. Crystallography was developed to gain insights into the arrangement of atoms and molecules in materials – that led eventually to the discovery of DNA. Procedures for dating rocks by radioactive decay were developed. Astrophysicists were able to frame testable hypotheses. The processes by which nuclei are synthesised in stars were charted. The life cycles of stars were elucidated. How the primordial universe generated matter became knowable. Cosmologists were able to frame and test rational hypotheses about the origin of the universe.

Atomic Structure of the Elements

There are 92 naturally occurring elements, ranging from hydrogen (H), the lightest, to uranium (U), the heaviest. Among the others are: Helium (He), Carbon (C), Nitrogen (N), Oxygen (O), Chlorine (Cl), Sodium (Na), Aluminium (Al), Silicon (Si), Sulphur (S), Iron (Fe), Copper (Cu), Silver (Ag), Gold (Au), Mercury (Hg) and Lead (Pb).

Each of the elements has a definitive atomic structure – they can be arranged, according to their structural similarities, into a periodic table such as below. Note the elements heavier than Uranium in the table – they have been synthesised in nuclear reactors and atomic accelerators.

The Periodic Table of the Elements

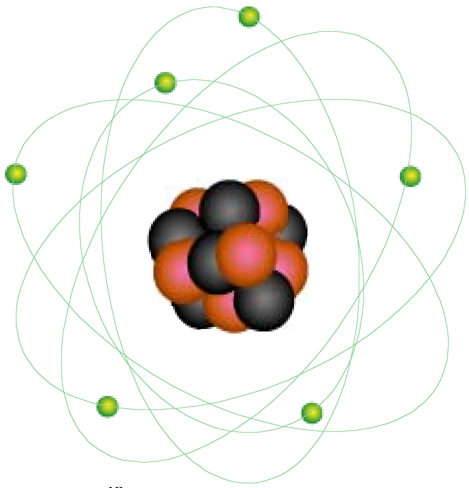
1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012182											5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989770	12 **Mg** Magnesium 24.3050											13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933200	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90545	56 **Ba** Barium 137.327		72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)		104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				
		57 **La** Lanthanum 138.9055	58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967	
		89 **Ac** Actinium (227)	90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)	

An atom has a compact positive nucleus surrounded by a diffuse shell of negative electrons.

The nucleus contains both protons with positive charges and neutral particles, neutrons.

A proton's charge is equal, but opposite to the negative charge of an electron.

Atoms have equal numbers of protons and electrons. The two sets of charges balance out – intact atoms are neutral.

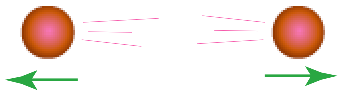


Carbon (^{12}C) has six protons, six neutrons and 6 electrons.

Protons and neutrons are of a similar size and mass and are quite heavy. Electrons are much smaller and have a minute mass, 1/1800 that of a proton.

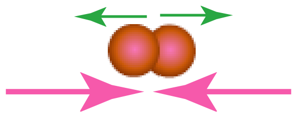
The positively charged protons in a nucleus attract an equal number of negatively charged electrons to form an atom. Quantum restraints prevent electrons from spiralling into the nucleus – they settle into orbitals, a considerable distance from the nucleus. Rapidly moving electrons enclose the nucleus in cloud-like shells that give atoms their size.

At inter-atomic distances, protons repel each other by electric force.



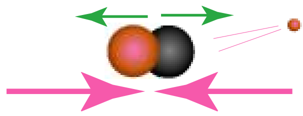
At inter-atomic distances
protons are repelled by electric force

If protons are forced to within nuclear distances, an attractive atomic force, strong enough to overpower the electric repulsive force begins to act and binds the protons into a nucleus.



At nuclear distances
strong atomic force binds protons together

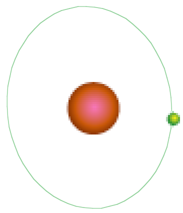
When protons are brought together, the repulsive force struggles against the binding force, stressing the protons. The tension is released when some of them shed charge and transform into neutrons by ejecting electron-sized, positively charged particles called positrons.



A neutron is formed as a positron is emitted
to carry away a positive charge
and relieve nuclear stress

To force free protons into a nucleus requires extraordinarily high temperatures and pressures. Such conditions are found in the cores of stars.

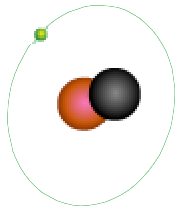
Hydrogen is the simplest atom. Its nucleus has only a proton. The nuclei of all other atoms have both protons and neutrons.



Hydrogen atom (^{1}H)
One proton

Atoms with the same number of protons and different numbers of neutrons are called isotopes.

Hydrogen forms three isotopes. Hydrogen (^{1}H) has one proton in the nucleus. Deuterium (^{2}H) has a proton and a neutron. Tritium (^{3}H) has a proton and two neutrons.

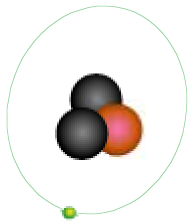


Deuterium atom (^{2}H)
an isotope of hydrogen
one proton
one neutron

The number of protons in an atom is called the atomic number of the atom. Every element has a unique atomic number. Hydrogen has an atomic number of 1.

The total of the protons and neutrons in a nucleus is an approximate guide to an atom's mass and is termed the atomic weight.

Isotope	*Atomic Number*	*Atomic Weight*
hydrogen	1	1
deuterium	1	2
tritium	1	3



Tritium atom (^{3}H)
an isotope of hydrogen
one proton
two neutrons

How the Sun Creates Energy

The extraordinarily high temperature and pressure in the cores of stars triggers the fusion of hydrogen into helium. There are two stellar fusion processes:

- The Proton-Proton Chain (PP Chain), which occurs in the cores of small stars.
- The Carbon-Nitrogen-Oxygen Cycle (CNO cycle), which occurs only in larger stars.

In the Sun's core, the main process is the PP Chain. Each step of the chain produces a heavier particle and releases energy.

The Steps of the PP Process

Step One – produce deuterium

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + \text{positron} + \text{neutrino}$$
$$\text{positron} + \text{electron} \rightarrow \text{gamma rays}$$

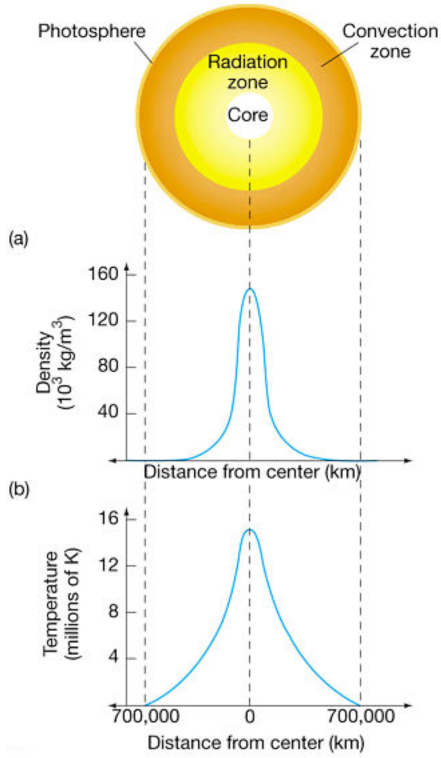
Step Two – produce light helium

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \text{gamma ray}$$

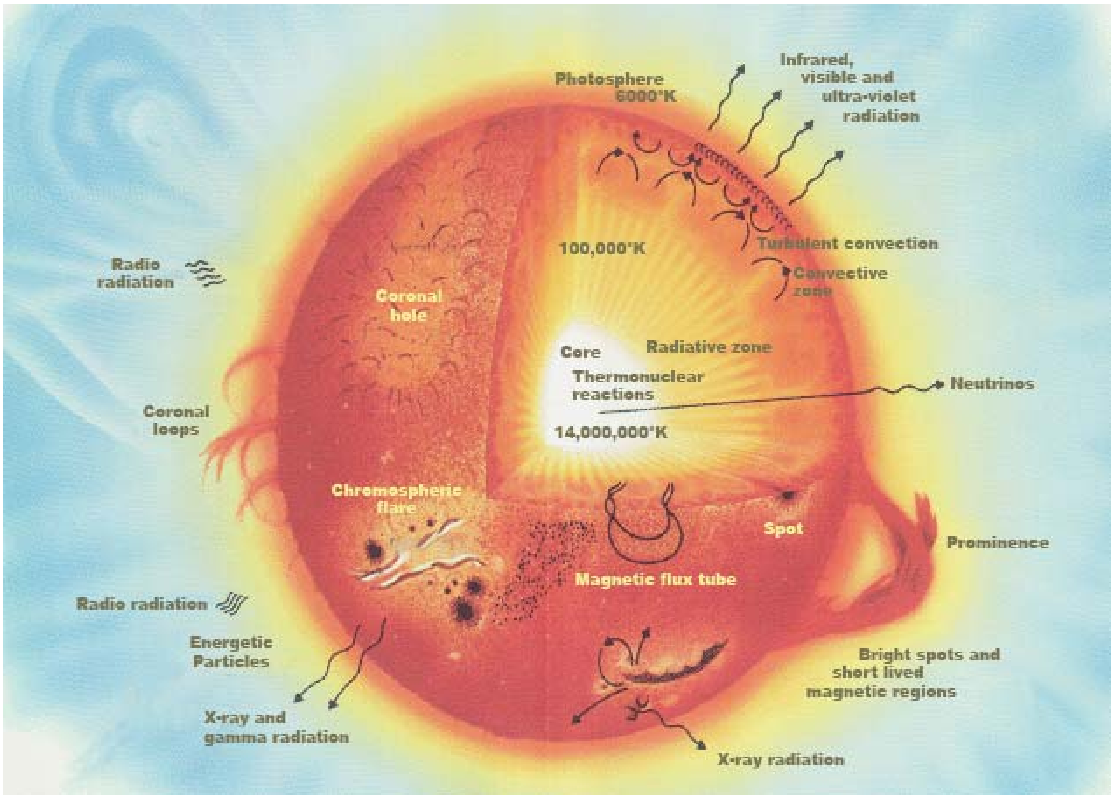
Step Three – produce helium

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$$

The end result is the fusion of hydrogen into helium.



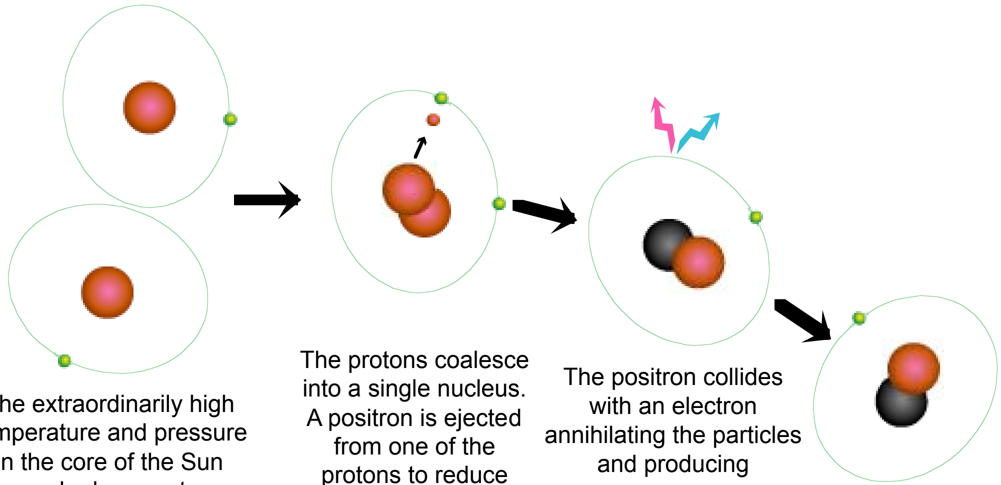
The temperature and pressure at the core of the Sun is extraordinarily high.



Solar Processes, Ulysses Site

The Steps of the PP Process – illustrated

Step One - produce deuterium



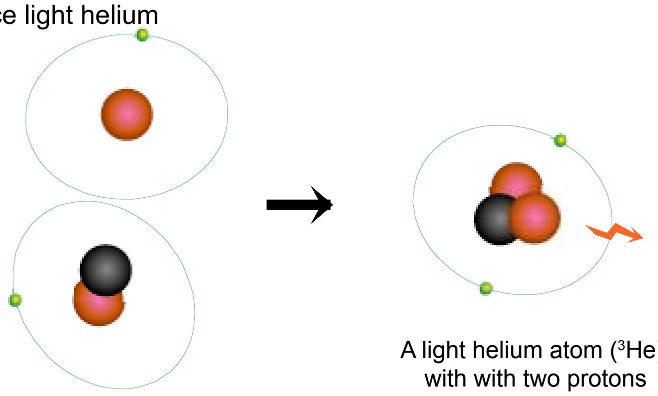
The extraordinarily high temperature and pressure in the core of the Sun forces hydrogen atoms together.

The protons coalesce into a single nucleus. A positron is ejected from one of the protons to reduce nuclear stress.

The positron collides with an electron annihilating the particles and producing gamma rays.

A deuterium atom (^{2}H) is the result.

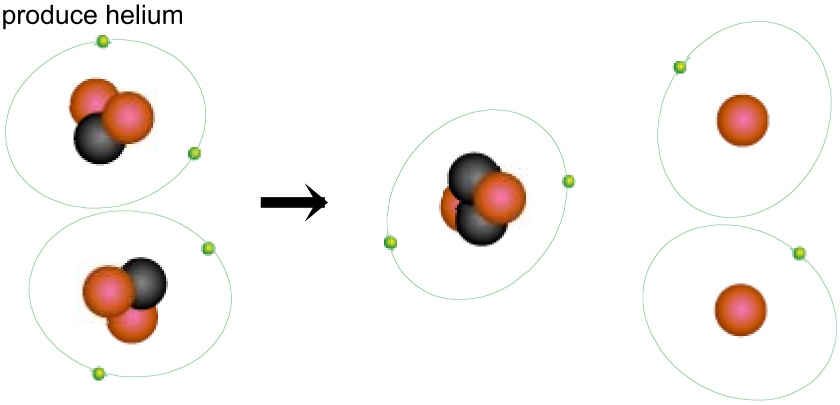
Step Two- produce light helium



A hydrogen atom (^{1}H) combines with a deuterium atom (^{2}H)

A light helium atom (^{3}He), with with two protons an one neutron, is formed. A gamma ray is released.

Step Three - produce helium

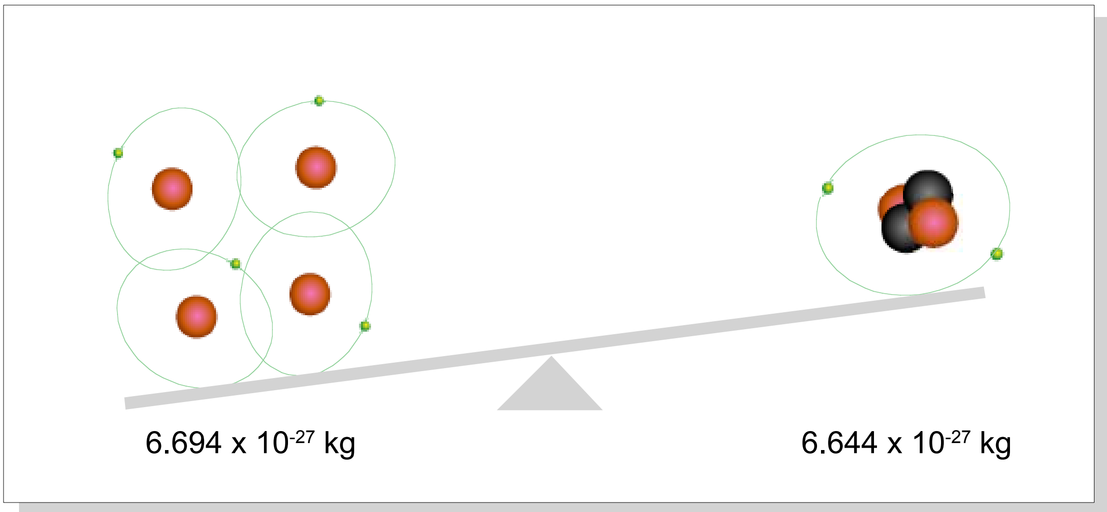


Two light helium (^{3}H) nuclei combine.

The new nucleus immediately disintegrates into a helium atom (^{4}He) and a pair of hydrogen atoms (^{1}H) The high velocities of the product atoms add to the energy produced by the fusion process.

Note: Steps one and two have to occur twice as often as step three in order to produce the required number of ^{3}He atoms.

The outcome of the PP Chain: four hydrogen atoms fuse to form one helium atom and release an amount of energy.



Mass is lost when hydrogen fuses into helium

The four hydrogen atoms that fuel the process weigh slightly more than the helium atom produced. The amount of mass lost is directly related to the amount of energy produced. The relationship is given by Einstein's equation:

$$E = mc^2$$

Where:
- E is the energy produced
- m is the amount of mass lost (0.05×10^{-27} kg)
- c is the velocity of light (3×10^8 metres per second)

On substituting the above values, we get

$$E = 0.05 \times 10^{-27} \times \left(3 \times 10^8\right)^2$$
$$= 4.5 \times 10^{-12} \text{ joule}$$

A kilogram of hydrogen contains 6×10^{26} atoms.
Dividing by 4 gives the number of helium atoms it would produce: 1.5×10^{26}
For each atom of helium, 4.5×10^{-12} joule is released
The total energy released is therefore $1.5 \times 10^{26} \times 4.5 \times 10^{-12} = 6.7 \times 10^{16}$ joule

Fusing a kilogram of hydrogen produces 997 grams of helium. The missing 3 grams is converted to heat and light energy. The amount of energy produced is equivalent to that released by burning 100,000 tonne of coal.

The Sun transforms 4.5×10^6 tonne of matter per second, (equivalent to 4 million car bodies per second). The Sun has been fusing hydrogen for nearly 5 billion years and has enough fuel left to burn for a further 5 billion years.