

Star Factories: Nuclear Fusion and the Creation of the Elements

Science In the River City workshop
3/22/11

Chris Taylor
Department of Physics and Astronomy
Sacramento State

Introductions!

Science Content Standards, Grades 9 - 12

Earth Sciences:

Earth's Place in the Universe

1.e *"Students know the Sun is a typical star and is powered by nuclear reactions, primarily the fusion of hydrogen to form helium."*

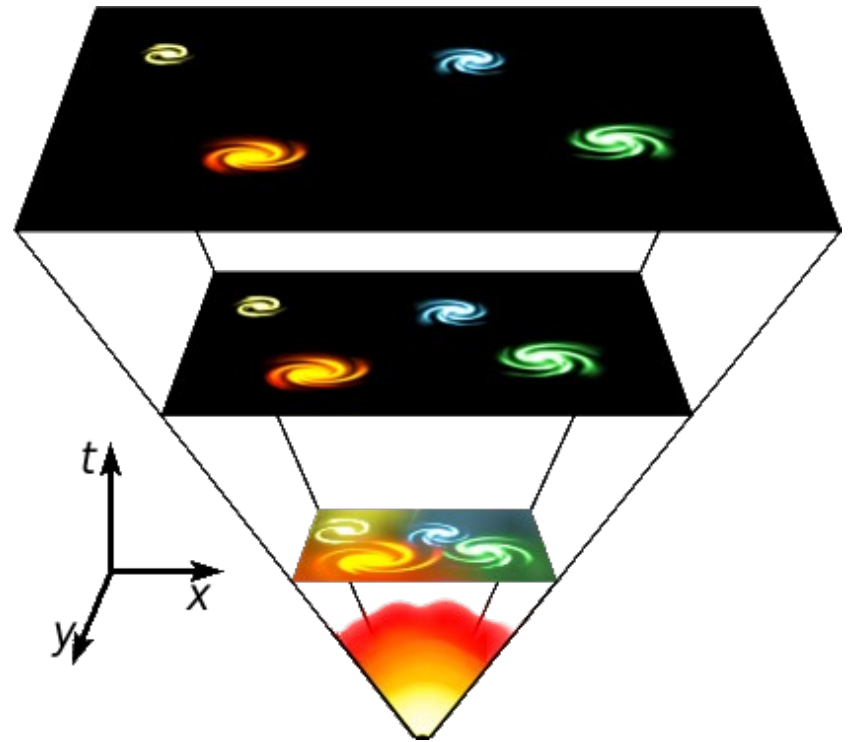
2.c *" Students know the evidence indicating that all elements with an atomic number greater than that of lithium have been formed by nuclear fusion in stars."*

Three topics tonight:

- 1) how do we know all the heavier elements are made in stars? (*Big Bang theory*)
- 2) How do stars make elements as heavy as or less heavy than iron?
(*Stellar nucleosynthesis*)
- 3) How do stars make elements heavier than iron? (*Supernovae*)

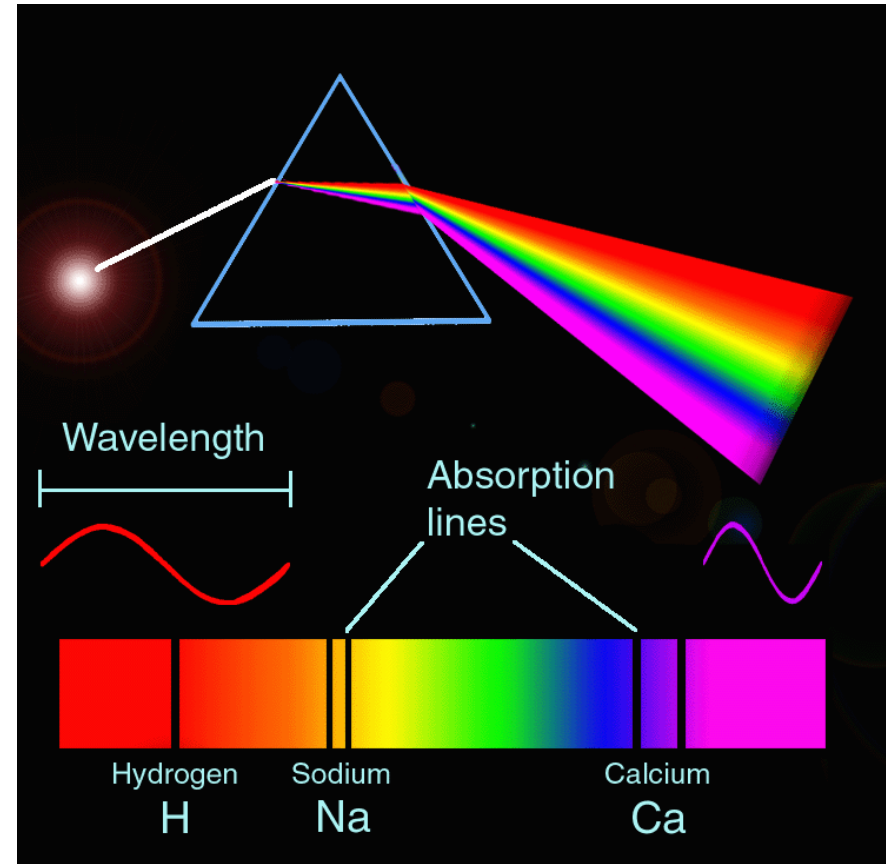
Big Bang Nucleosynthesis

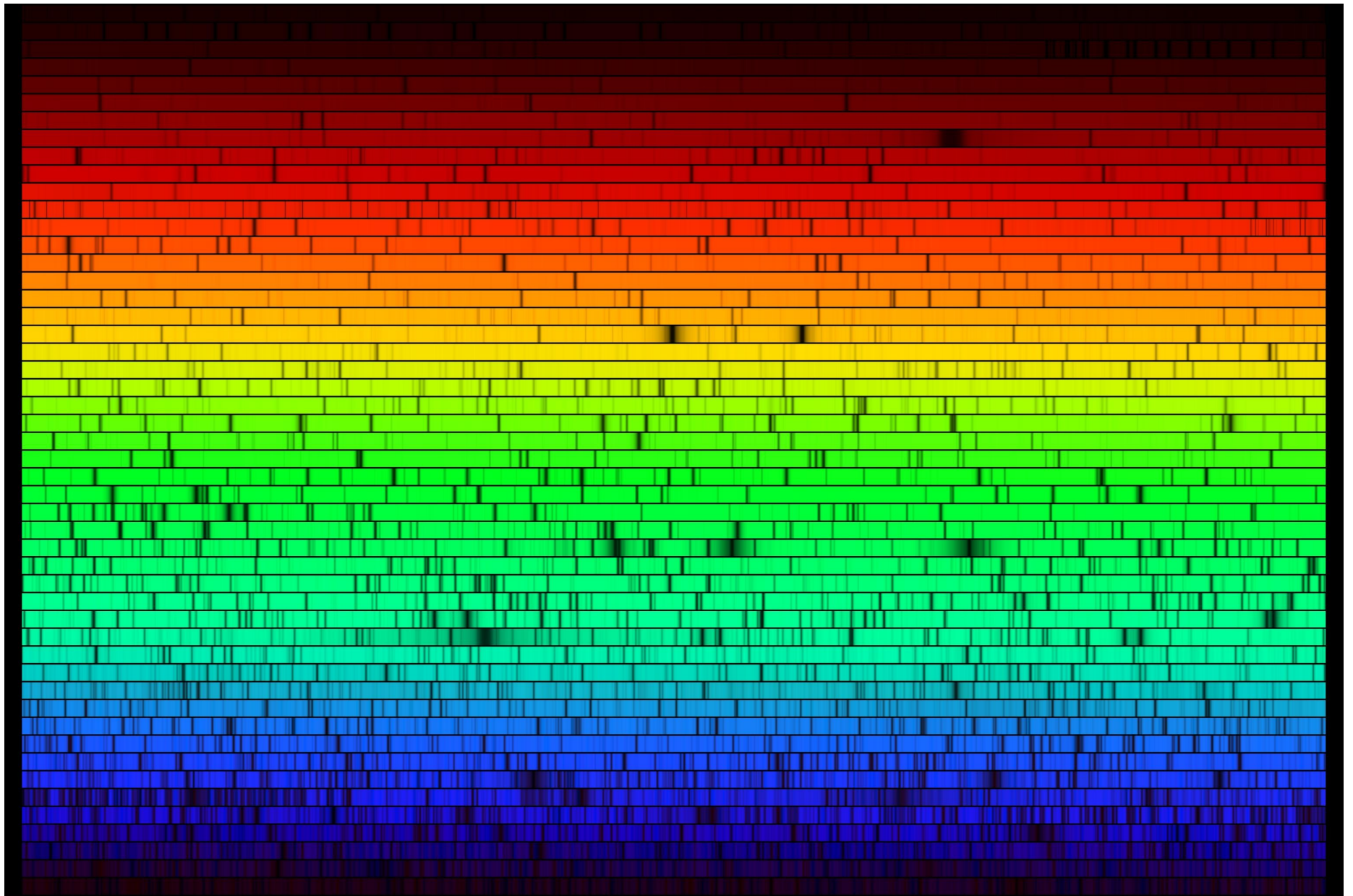
The Big Bang theory predicts that when the universe first formed, the only matter that existed was hydrogen, helium, and very tiny amounts of lithium. If this is true, then all other elements must have been created in stars.



Astronomers use spectroscopy to examine the light emitted by distant stars to determine what kinds of atoms are in them.

We've learned that most stars contain nearly every element in the periodic table.





The spectrum of the Sun

In order to measure what kinds of atoms were around in the earliest days of the Universe, we look for stars that were made out of fresh, primordial gas.

The closest we can get to this is looking at dwarf galaxies, which show extremely low levels of elements heavier than helium.



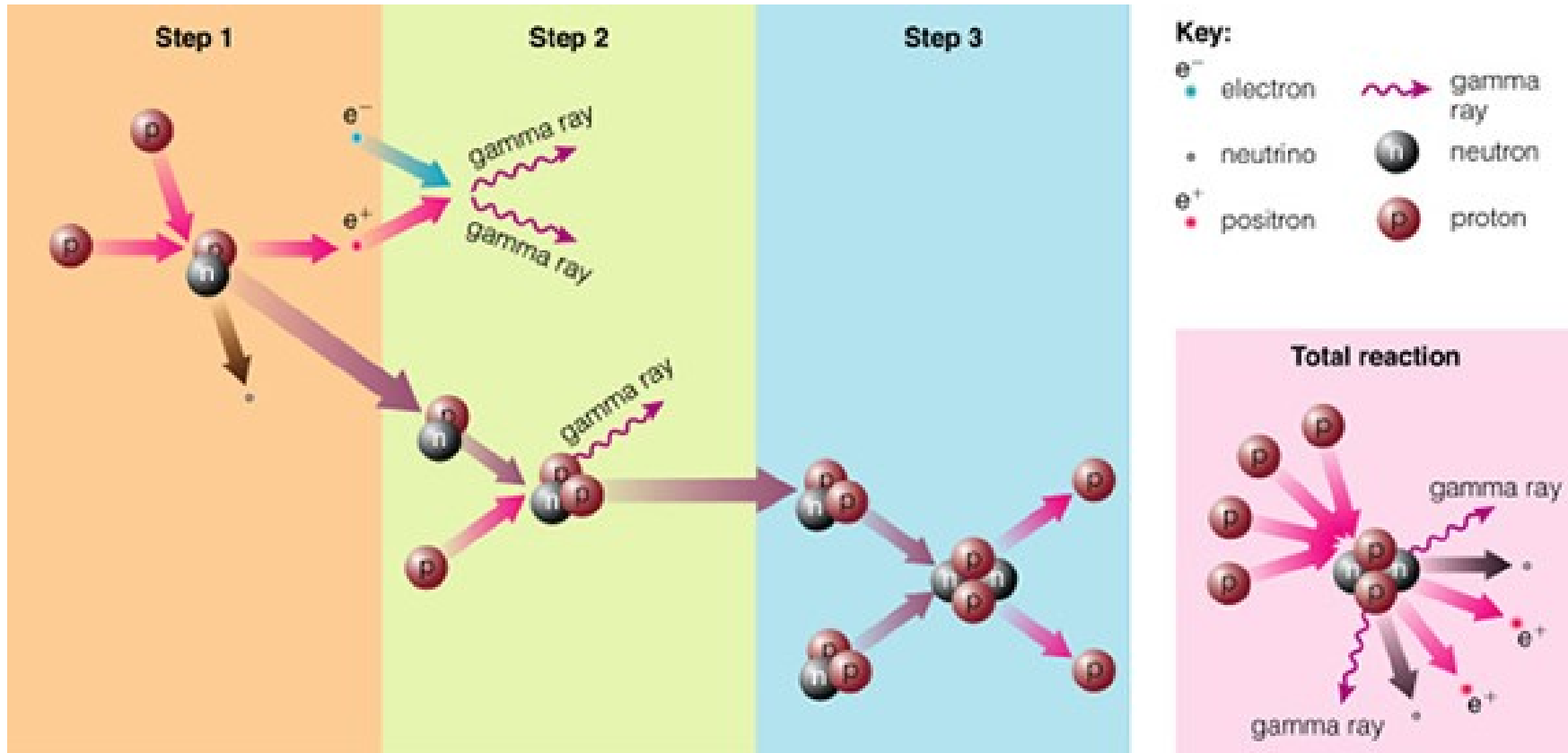
*

Stellar Nucleosynthesis

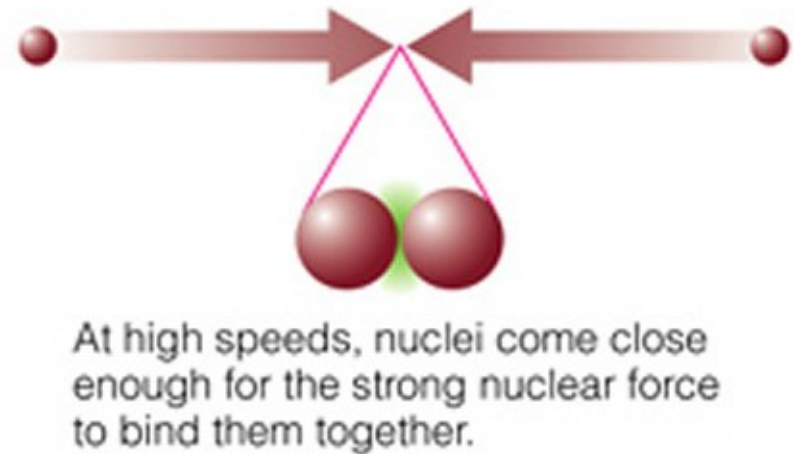
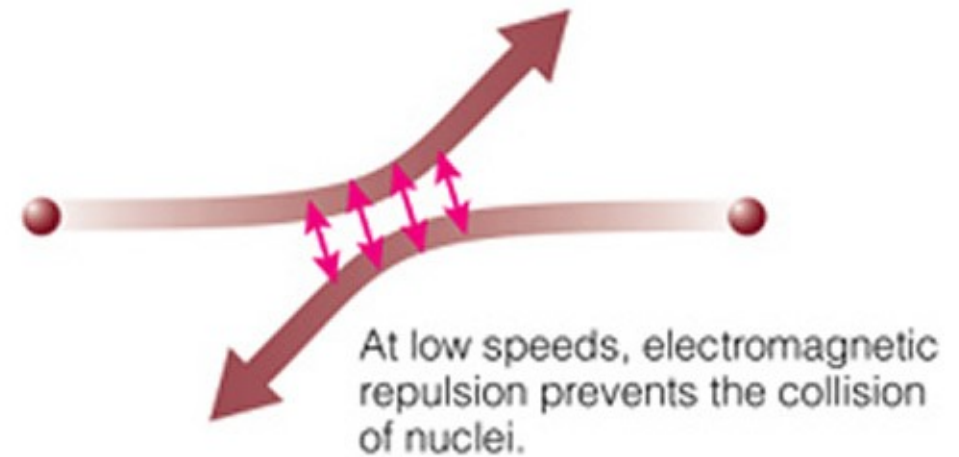
If heavy elements didn't get formed during the Big Bang, then where do they come from?



The Proton-Proton Chain



In fusion, atomic nuclei are smashed together at speeds high enough to overcome the electric repulsion of their positive charges. The nuclei then join together to form a single larger nucleus.



* The only place we know that fusion can build heavy elements is inside the cores of stars. The question now is:

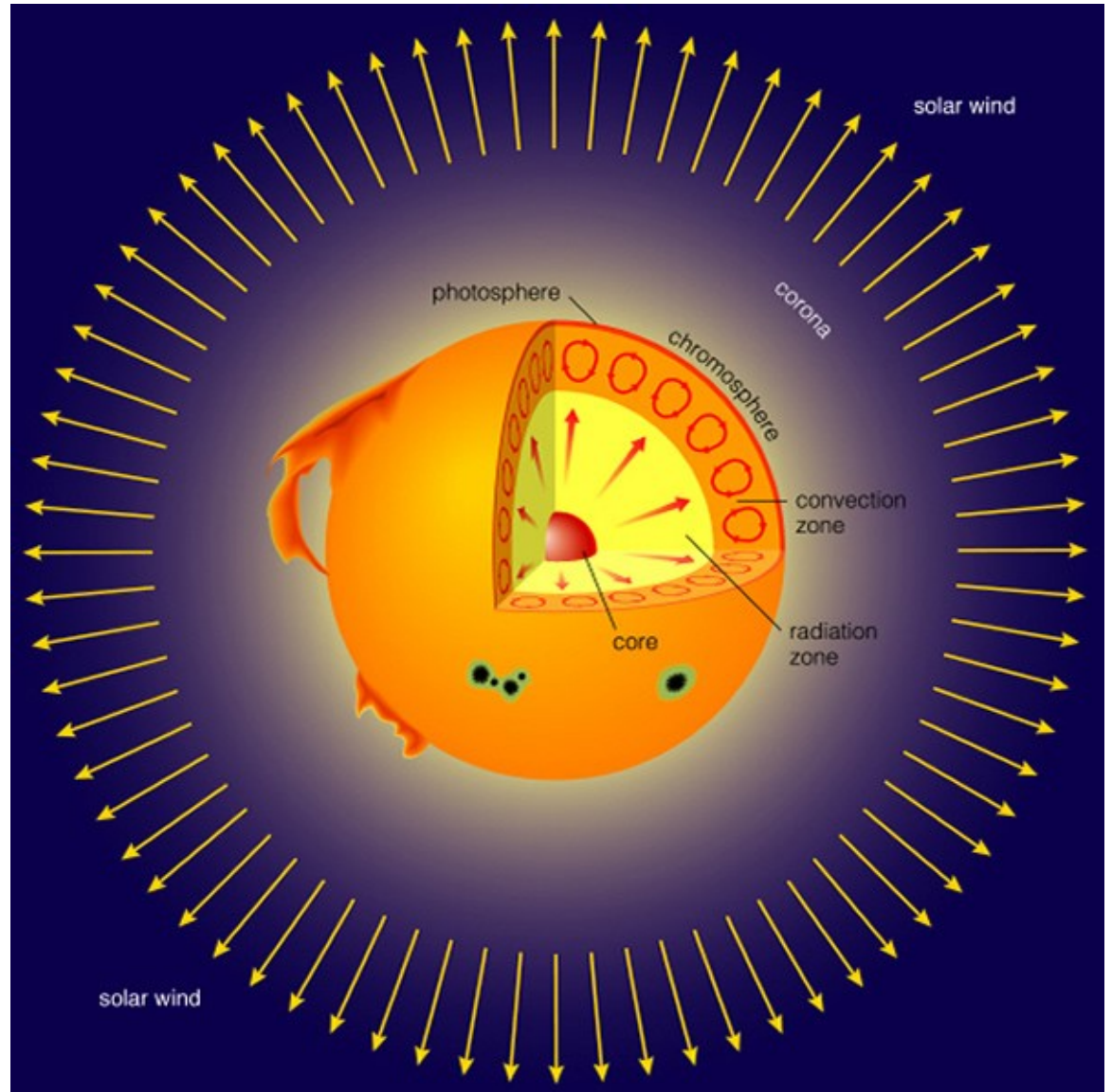
What is it about the environment inside stars that makes nuclear fusion possible?

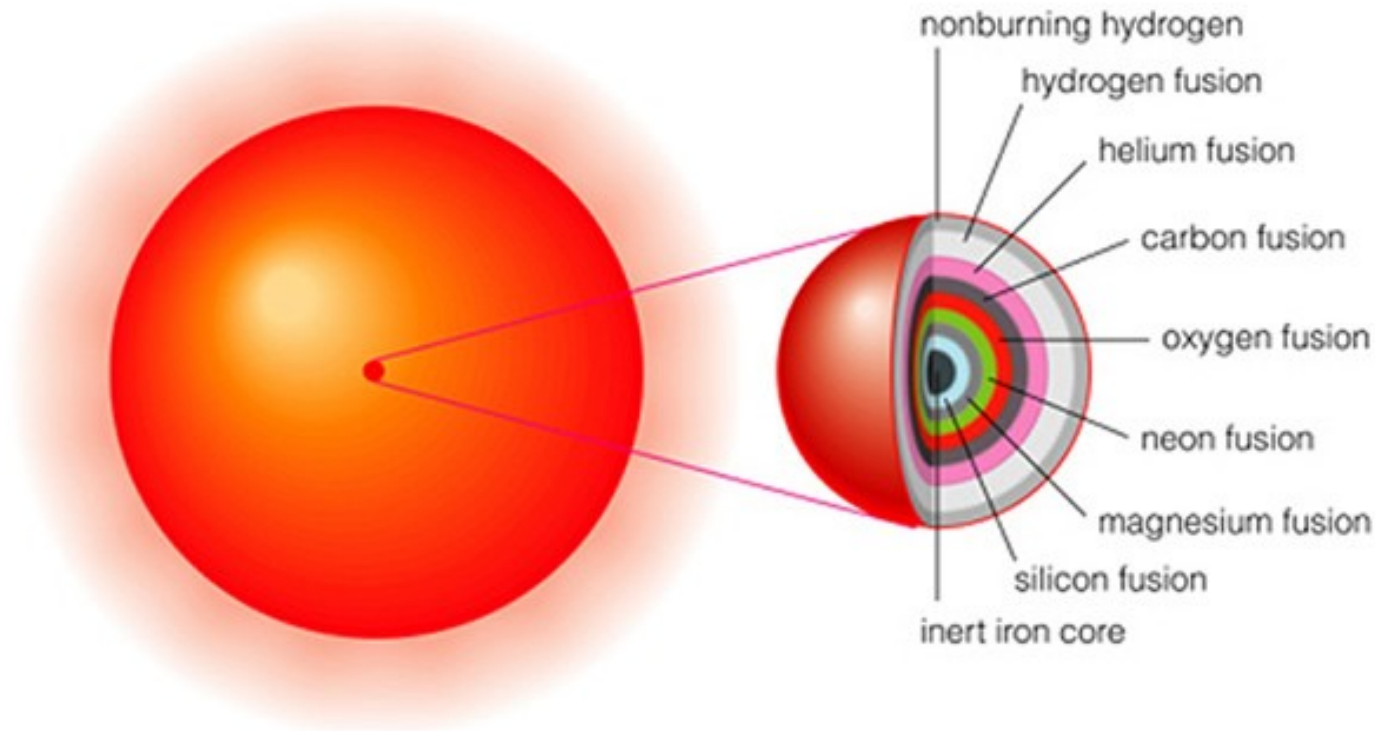
High temperature; and

high density.

Demo

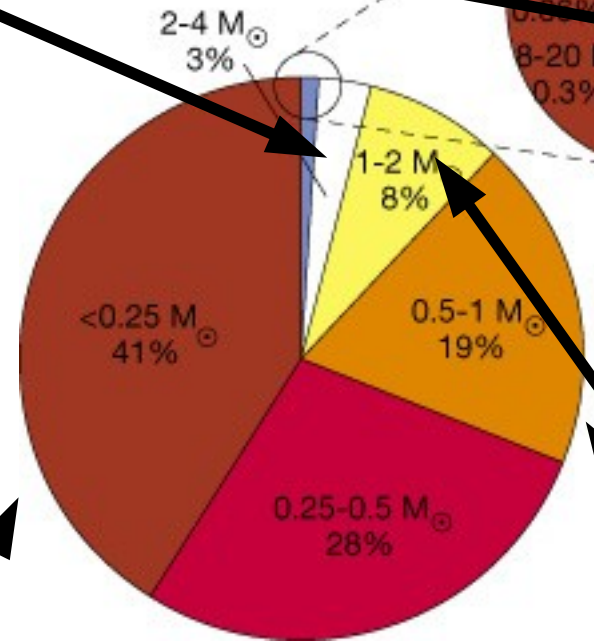
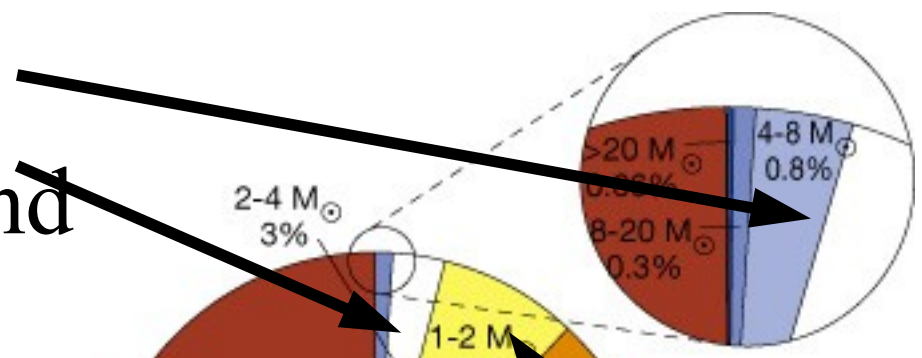
Stars like the Sun will make helium in their cores until the hydrogen fuel runs out. Some, but not all, stars will then switch over to fusing helium into carbon. This is the origin of all carbon in the Universe.





The higher the mass of the star, the heavier elements it can create in its core. This is because heavy element fusion requires higher temperatures, which only the most massive stars can attain.

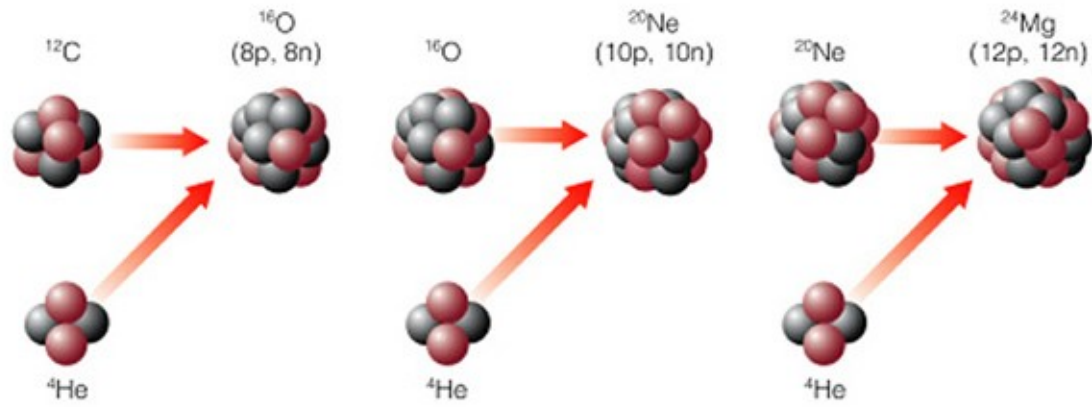
Helium,
carbon and
oxygen.



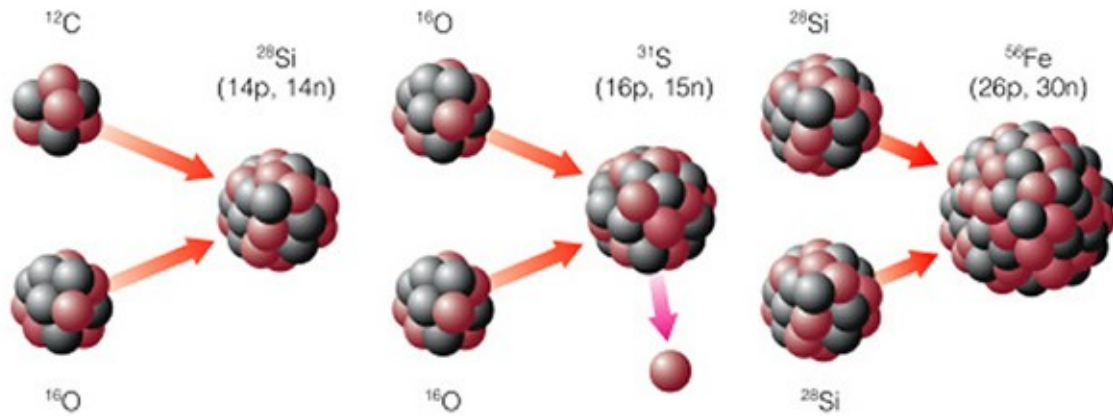
Helium only

Helium and
carbon

Helium-capture reactions

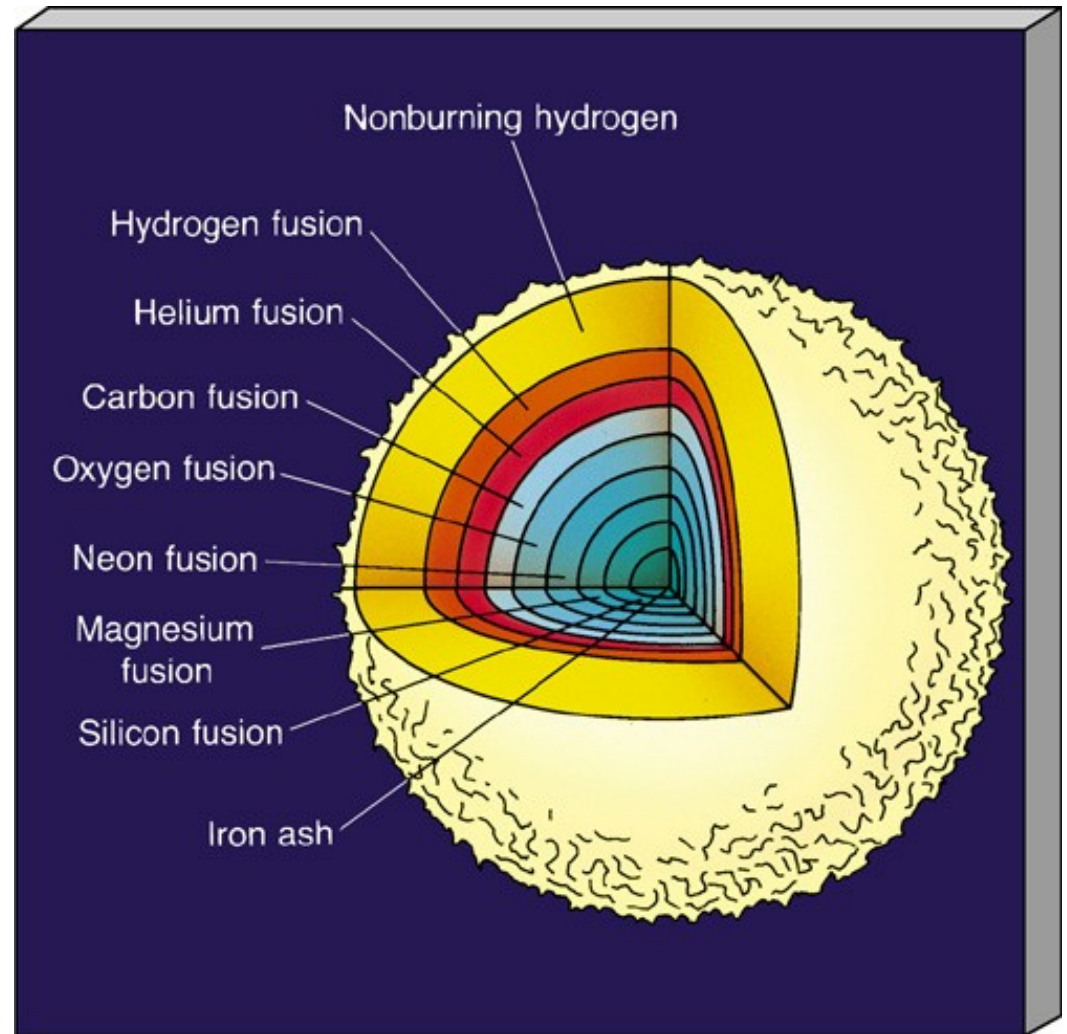


Other reactions



The highest mass stars can make all elements up to and including iron in their cores.

But iron is the heaviest element they can make. Fusion of iron does not create energy, and without an energy supply, the star will soon die.



* **Nucleosynthesis in Supernovae**

If stars can only fuse elements up to and including iron (Number 26 on the periodic table) then where do all the gold, silver, lead, uranium, etc... come from?



Supernova Explosion

Inert iron core stops producing energy, but continues to produce neutrinos which release energy from core

Densities climb, protons and electrons combine to produce neutrons and more neutrinos

Sudden loss of energy causes core to collapse from lack of pressure support

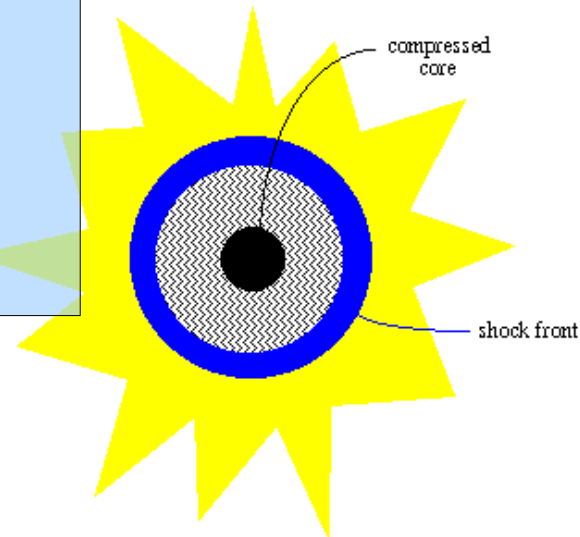
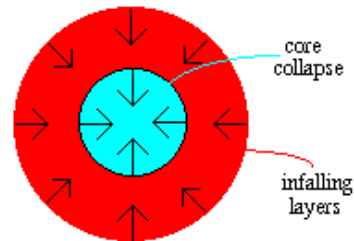
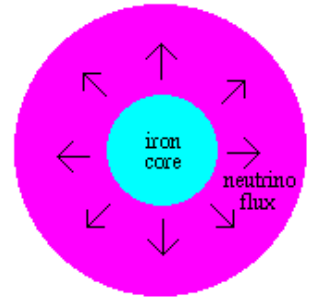
Regions around core are unsupported and plunge onto core at speeds up to 15% the speed of light

Neutron densities are so high in core that it is incompressible and rigid. Infalling layers strike core and rebound.

In a fraction of a second, a wave of matter forms a shock front and moves outward towards stellar surface.

Shock wave hits surface of star and explodes

Inward shock compresses remaining stellar core into neutron star or black hole



When a high mass star's core runs out of fusion fuel, the core collapses, causing the regions near the core to fall in and bounce off the core.

This creates an outward moving shockwave of atoms.

Demo

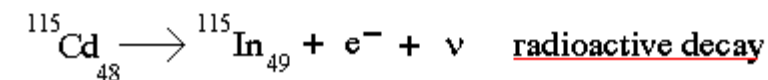
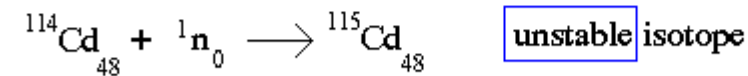
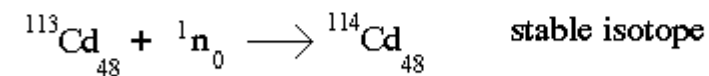
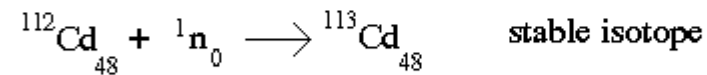
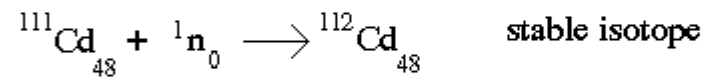
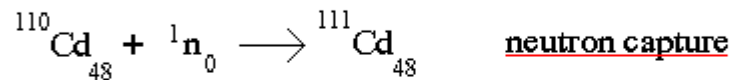
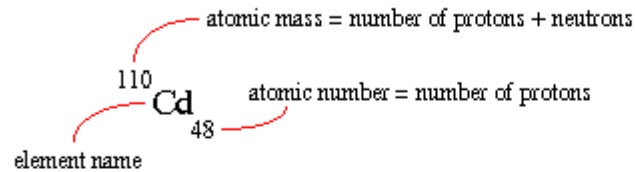
The R-Process

When the supernova explodes, large numbers of neutrons are shot out of the interior of the star at high velocities. Think of these like pellets in a shot gun shell that has been fired.

These neutrons pass through the outer regions of the star, colliding with the atoms already there (mostly hydrogen). The collisions happen very rapidly and quickly build up very large atoms.

Nucleosynthesis by Neutron Capture

construction of elements beyond iron involves the capture of a neutron to produce isotopes. Unstable isotopes decay into new elements



Fusion in stellar cores

hydrogen 1 H 1.0079																	helium 2 He 4.0026				
lithium 3 Li 6.941	beryllium 4 Be 9.0122															boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305															aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80				
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29				
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]			
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]	ununquadium 114 Uuq [289]								

* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Fusion in supernova explosions

Thanks!