hydrogen and helium burning

We turn now to look at the most important nuclear reactions which occur in stars.

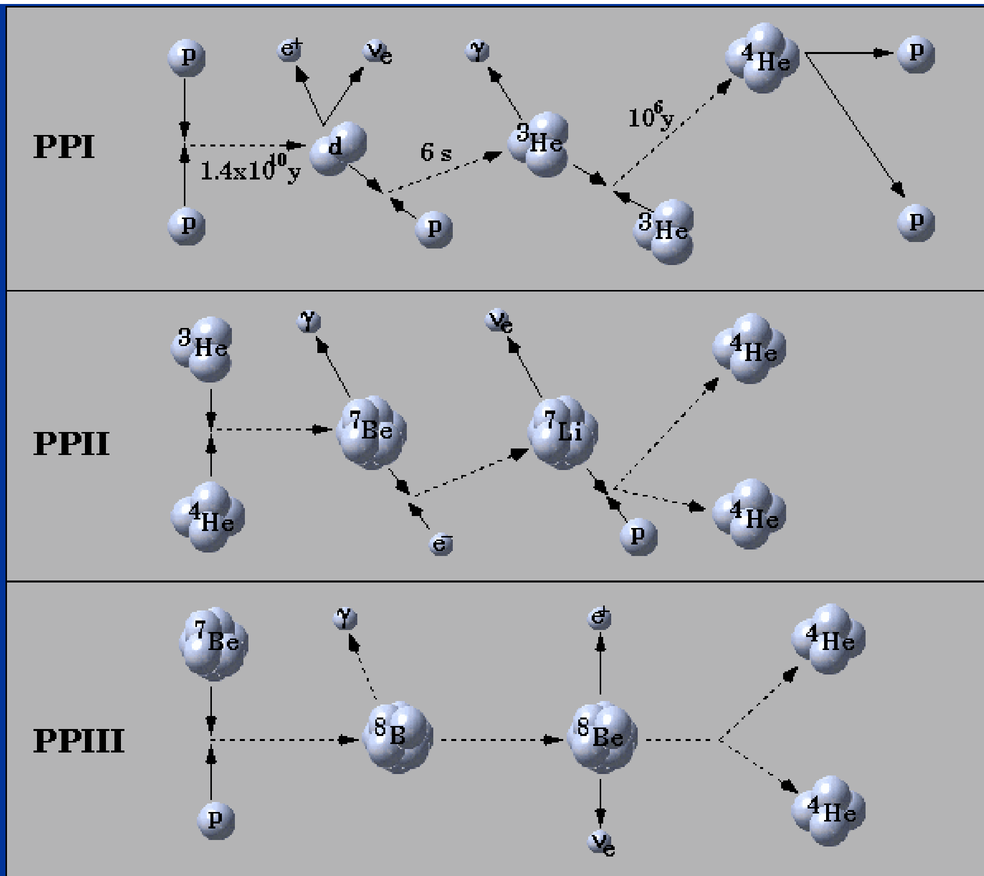
hydrogen burning reactions

The most important series of fusion reactions are those converting hydrogen to helium in a process known as *hydrogen burning*. The chances of four protons fusing together to form helium in one go are completely negligible. Instead, the reaction must proceed through a series of steps. There are many possibilities here, but we will be looking at the two main hydrogen-burning reaction chains: the *proton-proton (PP) chain* and the *carbon-nitrogen (CNO) cycle*. The PP chain divides into three main branches, which are called the PPI, PPII and PPIII chains. The first reaction is the interaction of two protons (p or ^{1}H) to form a nucleus of heavy hydrogen (deuteron, d, or ^{2}H), consisting of one proton and one neutron, with the emission of a positron (e^{+}) and a neutrino (ν_e). The deuteron then captures another proton and forms the light isotope of helium with the emission of a γ-ray. The ^{3}He nucleus can then either interact with another ^{3}He nucleus or with a nucleus of ^{4}He (an α particle), which has either already been formed or has been present since the birth of the star. The former case is the last reaction of the PPI chain, whereas the latter reaction leads into either the PPII or the PPIII chain, as shown below:

PPI chain		**PPII chain**		**PPIII chain**	
		this starts with reactions 1 and 2		this starts with reactions 1, 2 and 3'	
1	$p + p \rightarrow d + e^{+} + \nu_e$	**3'**	$^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be} + \gamma$	**4''**	$^{7}\text{Be} + p \rightarrow {}^{8}\text{B} + \gamma$
2	$d + p \rightarrow {}^{3}\text{He} + \gamma$	**4'**	$^{7}\text{Be} + e^{-} \rightarrow {}^{7}\text{Li} + \nu_e$	**5''**	$^{8}\text{B} \rightarrow {}^{8}\text{Be} + e^{+} + \nu_e$
3	$^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + p + p$	**5'**	$^{7}\text{Li} + p \rightarrow {}^{4}\text{He} + {}^{4}\text{He}$	**6''**	$^{8}\text{Be} \rightarrow {}^{4}\text{He} + {}^{4}\text{He}$

It can be seen that there is another choice in the chain when ^{7}Be either captures an electron to form ^{7}Li in the PPII chain or captures another proton to form ^{8}B in the PPIII chain. At the end of the PPIII chain, the unstable nucleus of ^{8}Be breaks up to form two ^{4}He nuclei. The PP chain reactions are summarized pictorially in figure 17.

Figure 17: The proton-proton chain.



The reaction rate of the PP chain is set by the rate of the slowest step, which is the fusion of two protons to produce deuterium. This is because it is necessary for one of the protons to undergo a β^+ decay:

$p \rightarrow n + e^+ + \nu_e$.

This reaction occurs via the weak nuclear force and the average proton in the Sun will undergo such a reaction approximately once in the lifetime of the Sun, i.e. once every 10^{10} years. The subsequent reactions occur much more quickly, with the second step of the PP chain taking approximately 6 seconds and the third step approximately 10^6 years in the Sun.

The relative importance of the PPI and PPII chains depend on the relative importance of the reactions of ^{3}He with ^{3}He in PPI as compared to the reactions of ^{3}He with ^{4}He in PPII. For temperatures in excess of 1.4×10^7K, ^{3}He prefers to react with ^{4}He. At lower temperatures, the PPI chain is more important. The PPIII chain is never very important for energy generation, but it does generate abundant high energy neutrinos.

The other hydrogen burning reaction of importance is the CNO cycle:

CNO cycle

1 $^{12}C + p \rightarrow {}^{13}N + \gamma$

2 $^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

3 $^{13}C + p \rightarrow {}^{14}N + \gamma$

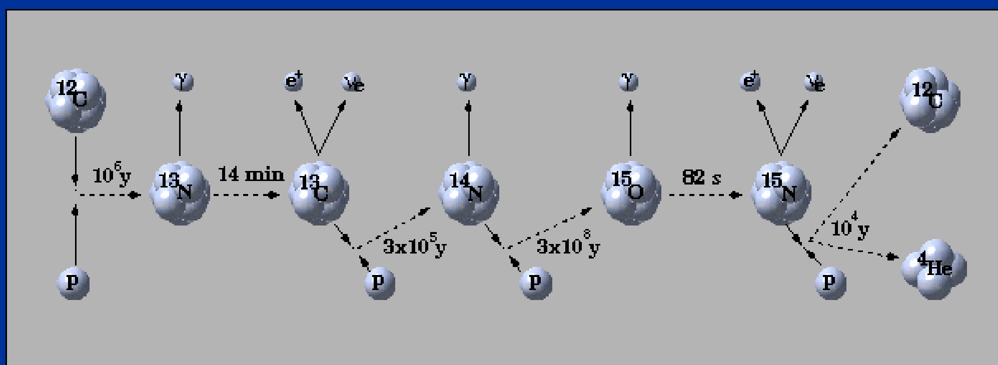
4 $^{14}N + p \rightarrow {}^{15}O + \gamma$

5 $^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

6 $^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

The reaction starts with a carbon nucleus, to which are added four protons successively. In two cases the proton addition is followed immediately by a β^+ decay, with the emission of a positron and a neutrino, and at the end of the cycle a helium nucleus is emitted and a nucleus of carbon remains. The reactions of the CNO cycle are shown pictorially in figure 18.

Figure 18: The CNO cycle.



Note that there are less important side reactions of the CNO cycle which are not listed here. Carbon is sometimes described as a *catalyst* in the above reaction because it is not destroyed by its operation and it must be present in the original material of the star for the CNO cycle to operate. When the cycle is working in equilibrium, the rates of all of the reactions in the chain must be the same. In order for this to be so, the abundances of the isotopes must take up values so that those isotopes which react more slowly have higher abundances. It can be seen from figure 18 that the slowest reaction in the CNO cycle is the capture of a proton by ^{14}N. As a result, most of the ^{12}C is converted to ^{14}N before the cycle reaches equilibrium and this is the source of most of the nitrogen in the Universe.

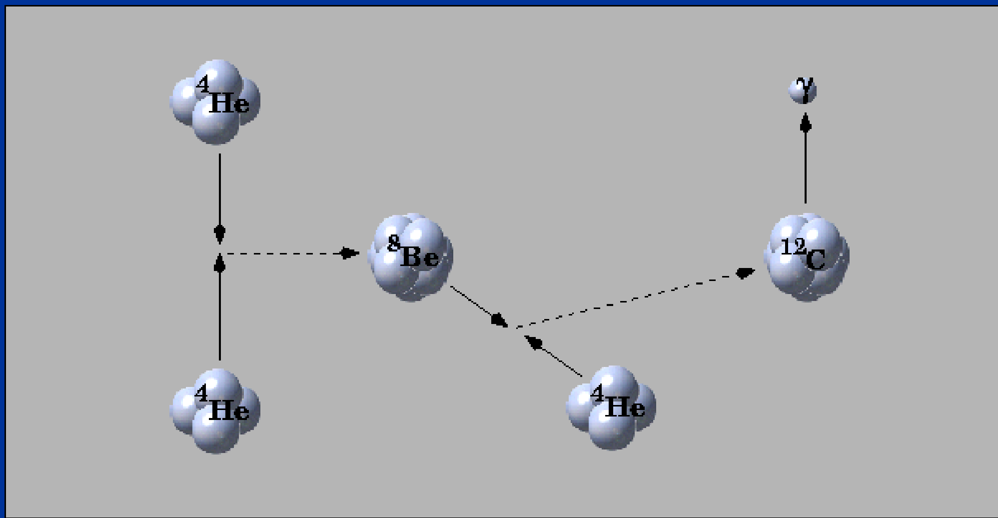
helium burning reactions

When there is no longer any hydrogen left to burn in the central regions of a star, gravity compresses the core until the temperature reaches the point where helium burning reactions become possible. In such reactions, two ^{4}He nuclei fuse to form a ^{8}Be nucleus, but this is very unstable to fission and rapidly decays to two ^{4}He nuclei again. Very rarely, however, a third helium nucleus can be added to ^{8}Be before it decays, forming ^{12}C by the so-called *triple-alpha reaction*:

$$^{4}He + {}^{4}He \rightarrow {}^{8}Be$$
$$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$$

The triple-alpha reaction is shown pictorially in figure 19. It can be seen that the reaction leaps from helium to carbon in one go, by-passing lithium, beryllium and boron. It is no coincidence, therefore, that these three elements are over 10^5 times less abundant by number than carbon in the Universe.

Figure 19: The triple alpha reaction.



Once helium is used up in the central regions of a star, further contraction and heating may occur, and that may lead to additional nuclear reactions such as the burning of carbon and heavier elements. We will not discuss these reactions here as the majority of the possible energy release by nuclear fusion reactions has occurred by the time that hydrogen and helium have been burnt.