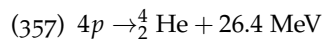

15 NUCLEAR REACTION PATHWAYS

15.1 Useful references

- Choudhuri, Sec. 4.3
- Kippenhahn, Weiger, and Weiss, 2nd ed., Secs. 18.5–18.6
- Hansen, Kawaler, and Trimble, Secs. 6.3–6.8

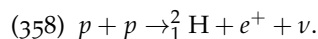
15.2 First fusion: the p-p chain

For stars with $M \lesssim 1M_{\odot}$, the dominant fusion pathway builds ${}^4_2\text{He}$ nuclei (i.e., α particles) from individual protons, and is termed the **p-p chain**. The overall reaction can be described as

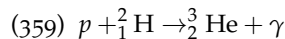


which liberates roughly 0.7% of the mass energy of the individual protons.

We've already encountered the first, weakest, and rate-limiting step in this process, namely

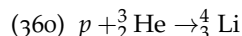


As we saw in the preceding chapter, the cross-section for this inverse beta-decay reaction is so low that a given proton will only undergo it in a \sim few Gyr. The next step,



happens very quickly – it takes only about 1.4 s in the Sun.

After ${}^3_2\text{He}$ is produced, there are three different pathways to ${}^4_2\text{He}$. These are termed pp1, pp2, and pp3. You might think that in a H-dominated universe we could proceed via



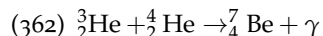
and another inverse beta decay, but ${}^4_3\text{Li}$ is highly unstable and its dominant decay mode is the emission of a proton, so that gets us nowhere.

Instead, we have to use larger building blocks and build up via collisions of ${}^3_2\text{He}$. If we have a paucity of ${}^4_2\text{He}$ (as was the case shortly after the Big Bang), then we must use the **pp1 pathway**:

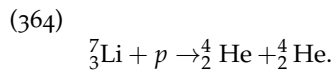
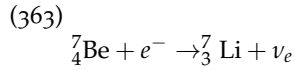


which produces roughly 70% of the total Solar luminosity.

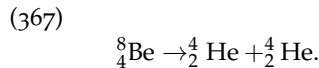
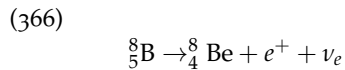
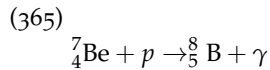
If ${}^4_2\text{He}$ is available (and especially at higher temperatures) the pp2 and pp3 pathways will dominate. These both begin via



and then branch off. In the Sun, almost all the rest of the luminosity comes from the pp2 pathway,

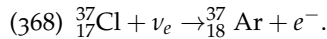


Whereas < 1% of the Sun's power comes from the pp3 pathway:



As noted above, all three pp chains convert protons into ${}^4_2\text{He}$ and so all release the same amount of energy, 26.4 MeV per α particle. But not all of that energy goes into heating the star (and ultimately to observable electromagnetic radiation): an appreciable fraction can be carried away by the neutrinos. The neutrino produced by the pp3 decay of ${}^8_5\text{B}$ can carry away up to 15 MeV (with an average of more like 7 MeV).

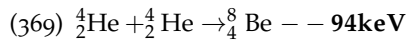
As a final aside, these pp3 neutrinos are energetic enough that they can be detected via



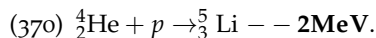
The argon produced is radioactive, and its decay can be easily detected. Neutrinos have tiny interaction cross-sections, but the chlorine needed to capture the neutrino is cheap in bulk – it's historically used in dry-cleaning.

15.3 The triple- α process

Via the p-p chains stars can build up helium nuclei (α particles) from elementary hydrogen nuclei (protons). Many heavier elements now populate the universe that weren't present immediately after the Big Bang. How were they created? The trouble is that both of the next two most likely reactions are endothermic, removing energy from the star instead of contributing to it:

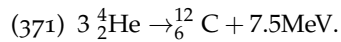


and



As with the first step in the pp chain, the solution turns out to be a relatively rare reaction; nonetheless, it is the most effective pathway available.

That is the **triple-alpha process**, in which three ^4_2He nuclei interact almost simultaneously, forming a $^{12}_6\text{C}$ nucleus. This reaction was predicted long before the reaction was known to be feasible, just because there was no other good explanation for the formation of heavier elements; it involves a resonance in the triple- α cross-section that allows this to proceed. The reaction therefore proceeds as



Note that whereas the pp chain has a mass-to-energy conversion efficiency of 0.7%, the triple- α process is an order of magnitude less efficient ($\sim 0.07\%$). So to support a star of given mass and temperature, the triple- α process would have to burn $\sim 10\times$ faster. This new reaction pathway also turns out to be highly temperature-sensitive, with

$$(372) \quad \epsilon_{3\alpha} \propto T^{40}$$

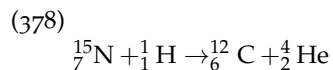
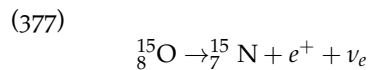
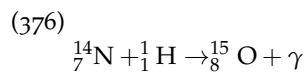
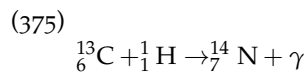
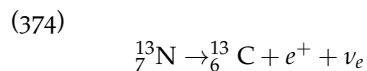
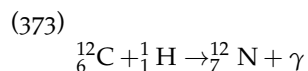
when temperatures approach $\sim 10^8$ K.

15.4 On Beyond ^{12}C

Once we have ^{12}C , multiple additional pathways open up for the stellar nucleosynthesis.

The CNO cycle

The first of these, the **CNO cycle**, is an alternative to the pp chains for producing ^4_2He from protons. However, the process here is rather less straightforward and requires the ^{12}C as a kind of catalyst. Multiple variants exist, but all rely on C to produce intermediate isotopes of N and O that are then broken back down to C in the production of an α particle. One common CNO cycle proceeds as follows:

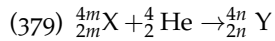


The CNO cycle does not become highly effective until temperatures are

somewhat higher than in the Sun's core. Thus at present only 1–2% of the Sun's He comes from the CNO cycle. But this ratio will increase as the Sun evolves and its central temperature steadily increases.

Alpha-process and higher-order nucleosynthesis

With a sufficient abundance of ${}^{12}_6\text{C}$ and ${}^4_2\text{He}$, **alpha-process nucleosynthesis** can begin and heavier elements can be rapidly produced. This requires higher temperatures and densities (and also higher ${}^{12}_6\text{C}$ abundances) than are found in the Sun's core, but the process becomes the dominant central energy source in the most massive stars. These reactions proceed in a much more straightforward manner than does the CNO cycle or p-p chains:



for $n = m + 1$, n and m both integers ≥ 3 .

Thus ${}^{16}_8\text{O}$, ${}^{20}_{10}\text{Ne}$, ${}^{24}_{12}\text{Mg}$, etc. can all be produced in this fashion. Other, related fusion processes also occur in stars that are more massive than the Sun. These are termed "_____ burning," where you can fill in the blank with your favorite choice of ${}^{12}_6\text{C}$, ${}^{16}_8\text{O}$, ${}^{32}_{16}\text{Si}$. Regardless of the specific pathway, Eq. 326 suggests that we will rapidly run out of road as we approach ${}^{56}_{26}\text{Fe}$ because it has the highest binding energy per nucleon.

As notes above for the triple-alpha process, each step in the nuclear burning chain becomes progressively less energy efficient. Fusing $\text{H} \rightarrow \text{He}$ converts 0.7% of mass into energy, $\text{He} \rightarrow \text{C}$ converts just 0.1%, and fusing $\text{C} \rightarrow \text{Fe}$ — the end of the line — converts only another 0.1%.