Nuclear Fusion in Stars

Within stars, the most common fusion reaction is the proton-proton chain, which is a series of reactions that convert hydrogen into helium. The overall reaction is:

$$6\,{}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} + 2e^{+} + 2\nu_{e}$$

Once enough helium has been produced, the helium nuclei themselves will have an appreciable chance of fusing. Two helium nuclei can undergo the interaction

$${}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{9}_{4}\mathrm{Be}\,.$$

However, this is extremely unstable and will quickly undergo the reverse reaction with a lifetime of around 10^{-16} s. If, however, the ${}^{8}_{4}\mathrm{Be}$ nucleus collides with another helium nucleus before it decays, it can undergo the reaction

$${}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{12}_{6}\mathrm{C}\,.$$

When enough carbon has been formed, a new cycle can begin in which ${}^{12}_{6}\mathrm{C}$ becomes a catalyst for the formation of ${}^{4}_{2}\mathrm{He}$ in the following chain:

$$\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{13}_{7}\mathrm{N} + \gamma \\
{}^{13}_{7}\mathrm{N} &\longrightarrow {}^{13}_{6}\mathrm{C} + e^{+} + \nu_{e} \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{14}_{7}\mathrm{N} + \gamma \\
{}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{15}_{8}\mathrm{O} + \gamma \\
{}^{15}_{8}\mathrm{O} &\longrightarrow {}^{15}_{7}\mathrm{N} + e^{+} + \nu_{e} \\
{}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}
\end{aligned}$$

The carbon acts as a catalyst; the ${}^{12}_{6}\mathrm{C}$ atom is consumed in the first reaction and regenerated in the last. The total energy released in this cycle is the same as in the proton-proton chain, but in the carbon cycle slightly more of that energy is lost via the neutrinos. However, the rate of the carbon cycle is much higher than the proton-proton chain.

Once the core of the star heats sufficiently, further reactions can occur to create heavier elements:

$$\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{16}_{8}\mathrm{O} \\
{}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{20}_{10}\mathrm{Ne} \\
{}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{24}_{12}\mathrm{Mg}
\end{aligned}$$

If these atoms are ejected into the cooler regions of the star, where the proton-proton cycle is still dominant, then they can capture protons to form elements with odd Z:

$$\begin{aligned}
{}^{16}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{19}_{9}\mathrm{F} \\
{}^{20}_{10}\mathrm{Ne} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{23}_{11}\mathrm{Na} \\
{}^{24}_{12}\mathrm{Mg} + {}^{1}_{1}\mathrm{H} &\longrightarrow {}^{27}_{13}\mathrm{Al}
\end{aligned}$$

As the core of the star heats further, these heavier nuclei can combine to form even larger elements, up to and including ${}^{56}_{26}\mathrm{Fe}$. However, we find that elements heavier than iron are not formed in stars via fusion.