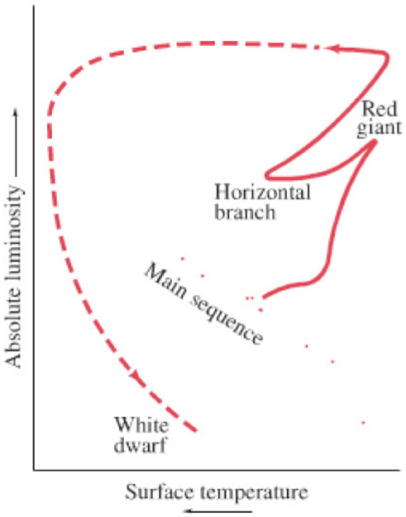

FIGURE 33–8 Evolutionary "track" of a star like our Sun represented on an H–R diagram.

Red giants

By this time the star has left the main sequence. It has become redder, and as it has grown in size, it has become more luminous. So it will have moved to the right and upward on the H–R diagram, as shown in Fig. 33–8. As it moves upward, it enters the **red giant** stage. Thus, theory explains the origin of red giants as a natural step in a star's evolution. Our Sun, for example, has been on the main sequence for about $4\frac{1}{2}$ billion years. It will probably remain there another 4 or 5 billion years. When our Sun leaves the main sequence, it is expected to grow in diameter (as it becomes a red giant) by a factor of 100 or more, swallowing up one or more of the inner planets (Mercury, Venus, maybe Earth).

If the star is like our Sun, or larger, further fusion can occur. As the star's outer envelope expands, its core is shrinking and heating up. When the temperature reaches about 10^8 K, even helium nuclei, in spite of their greater charge and hence greater electrical repulsion, can then reach each other and undergo fusion. The reactions are

$$\begin{aligned} {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{8}_{4}\mathrm{Be} \\ {}^{4}_{2}\mathrm{He} + {}^{8}_{4}\mathrm{Be} &\longrightarrow {}^{12}_{6}\mathrm{C} \end{aligned} \qquad \textbf{(33–2)}$$

with the emission of two γ rays. These two reactions must occur in quick succession (because ${}^{8}_{4}\mathrm{Be}$ is very unstable), and the net effect is

$$3\,{}^{4}_{2}\mathrm{He} \longrightarrow {}^{12}_{6}\mathrm{C}. \qquad (Q = 7.3\ \mathrm{MeV})$$

Nucleosynthesis

This fusion of helium causes a change in the star which moves rapidly to the "horizontal branch" on the H–R diagram (Fig. 33–8). Further fusion reactions are possible, with ${}^{4}_{2}\mathrm{He}$ fusing with ${}^{12}_{6}\mathrm{C}$ to form ${}^{16}_{8}\mathrm{O}$. In more massive stars, higher Z elements like ${}^{20}_{10}\mathrm{Ne}$ or ${}^{24}_{12}\mathrm{Mg}$ can be made. This process of creating heavier nuclei from lighter ones (or by absorption of neutrons which tends to occur at higher Z) is called **nucleosynthesis**.

White dwarfs

The final fate of a star depends on its mass. Stars can lose mass as parts of their envelope drift off into space. Stars born with a mass less than about 8 (or perhaps 10) solar masses eventually end up with a residual mass less than about 1.4 solar masses, which is known as the *Chandrasekhar limit*. For them, no further fusion energy can be obtained. The core of such a "low mass" star (original mass $\lesssim 8$ solar masses) contracts under gravity; the outer envelope expands again and the star becomes an even larger red giant. Eventually the outer layers escape into space, the core shrinks, the star cools, and typically follows the dashed route shown in Fig. 33–8, descending downward, becoming a **white dwarf**. A white dwarf with a mass equal to that of the Sun would be about the size of the Earth. A white dwarf contracts to the point at which the electron clouds start to overlap, but collapses no further because, as the Pauli exclusion principle claims, no two electrons can be in the same quantum state. Arriving at this point is called *electron degeneracy*. A white dwarf continues to lose internal energy by radiation, decreasing in temperature and becoming dimmer until its light goes out. It has then become a cold dark chunk of ash.

Production of heavy elements

Stars whose residual mass is greater than the Chandrasekhar limit of 1.4 solar masses (original mass greater than about 8 or 10 solar masses) are thought to follow a quite different scenario. A star with this great a mass can contract under gravity and heat up even further. In the range $T = 2.5-5 \times 10^9$ K, nuclei as heavy as ${}^{56}_{26}\mathrm{Fe}$ and ${}^{56}_{28}\mathrm{Ni}$ can be made. But here the formation of heavy nuclei from lighter ones by fusion, ends. As we saw in Fig. 30–1, the average binding energy per nucleon begins to decrease for A greater than about 60. Further fusions would *require* energy, rather than release it.

Elements heavier than Ni are thought to form mainly by neutron capture, particularly in supernova explosions. Large numbers of free neutrons, resulting from nuclear reactions, are present inside highly evolved stars and they can readily combine with, say, a ${}^{56}_{26}\mathrm{Fe}$ nucleus to form (if three are captured) ${}^{59}_{26}\mathrm{Fe}$, which decays to ${}^{59}_{27}\mathrm{Co}$. The ${}^{59}_{27}\mathrm{Co}$ can capture neutrons, also becoming neutron