Teacher notes
Topic E

A special nuclear energy level

The triple alpha process is an important sequence of nuclear fusion reactions that produce carbon in helium rich stellar cores. The process consists of the fusion reactions:

$${}^{4}_{2}\text{He} + {}^{4}_{2}\text{He} \rightarrow {}^{8}_{4}\text{Be} + \gamma$$

$${}^{4}_{2}\text{He} + {}^{8}_{4}\text{Be} \rightarrow {}^{12}_{6}\text{C} + \gamma$$

The net effect of these two reactions is to produce one carbon nucleus from the fusion of three helium nuclei.

The atomic masses are:

Helium	4.0026 u
Beryllium	8.0053 u
Carbon	12 u

So the overall process produces (3×4.0026 – 12)×931.5 = 7.27 MeV

The second reaction by itself produces (4.0026 + 8.0053 – 12)×931.5 = 7.36 MeV

But the second reaction is a problematic reaction because the beryllium nucleus is unstable with a half-life of about 8×10^{-17} s and so would decay before appreciable fusion reactions could take place to produce carbon in the quantities that are observed in stars.

It must be noted that the calculations we do to find the energy produced we assume that the fusing nuclei are at rest. In reality, the nuclei move and so their kinetic energy needs to be added to the energy produced. This is especially true for nuclei in stars where the high temperatures imply that the nuclei have large kinetic energies.

In 1953, Fred Hoyle (see the Teacher Note under General) calculated that in the case of this second reaction adding the kinetic energies would amount to an energy released of 7.65 MeV. Hoyle then postulated the existence of an excited state of carbon 12, with an energy of 7.65 MeV above the ground state (the state of normal C-12). At the time there was no evidence at all for the existence for such a carbon nuclear energy level. Hoyle convinced a team at Caltech to search for such a state. The team bombarded nitrogen-14 with deuterons and analyzed the spectrum of the produced carbon-12 and alpha particles. Sure enough, a state of energy precisely what Hoyle predicted was found.

This state, now called the Hoyle state of carbon, serves as an intermediary in the reaction ${}^{4}_{2}\mathrm{He} + {}^{8}_{4}\mathrm{Be} \to {}^{12}_{6}\mathrm{C} + \gamma$. The carbon produced is the Hoyle state which then decays by gamma emission to the normal ground state of carbon-12. The point is that by forming an excited energy state of carbon rather than the ground state the rate at which the reaction proceeds is 7 orders of magnitude faster than the rate for producing normal carbon directly. This is enough to account for the observed abundance of carbon.

Obviously, this is fundamental for life given the role of carbon for life!