reactions), fusion reactions have an energy *density* (energy output per unit mass of fuel) many times greater than fission reactions. This is because exothermic fission reactions occur with heavy nuclei, whereas exothermic fusion reactions occur with light nuclei, which are much smaller in mass. Fission reactions convert about 0.1 percent of matter into energy, whereas fusion reactions can reach as high as 0.7 percent. Only the direct conversion of mass into energy, such as the collision and annihilation between particles and antiparticles, is more energetic per unit mass than nuclear fusion.

Stellar Fusion

All stars are naturally occurring fusion reactors that operate at temperatures of millions of degrees. The majority of stars, including the Sun, are powered by hydrogen fusion. Other (mostly older) stars fuse heavier elements such as helium. The Sun is approximately 74 percent hydrogen and 25 percent helium by mass, with the remaining percent consisting of other trace elements. Every second, the Sun converts about 657 million tons of hydrogen into 653 million tons of helium through fusion reactions. The "lost" 4 million tons of particle mass is released as radiation energy and eventually reaches us as light and the "solar wind"—a collection of low-mass particles.

Stars are constantly collapsing inward due to the attractive force of gravity. The energy produced by nuclear fusion increases the outward pressure within the star, which opposes the tendency toward gravitational collapse. In order to maintain a sustainable rate of energy production, stars must be both hot enough and dense enough to ensure that particles will collide with a high enough frequency to cause fusion reactions.

The energy generated by the Sun is the result of a multi-step fusion reaction known as the **proton-proton chain** (FIGURE 35).

$$ {}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu \qquad (Q=0.42\ MeV) $$

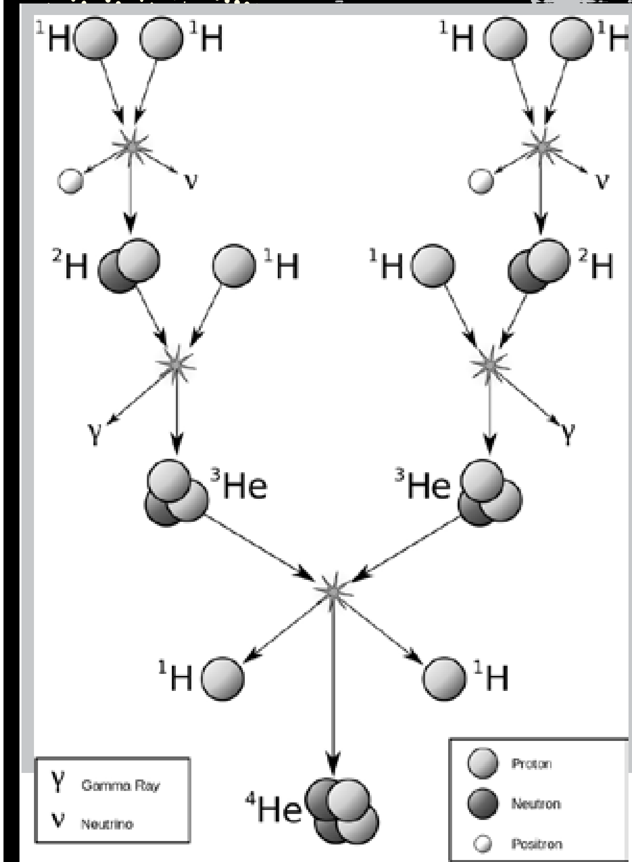
$$ {}^1_1H + {}^2_1H \rightarrow {}^3_2He + \gamma \qquad (Q=5.49\ MeV) $$

$$ {}^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H \qquad (Q=12.86\ MeV) $$

The net result of this series of reactions is the conversion of four protons into one helium-4 nucleus, two positrons, two neutrinos, and two gamma rays. Each iteration of the proton-proton cycle generates:

$$ \begin{array}{r} 12.86\ MeV \\ (2 \times 5.49\ MeV) \\ +(2 \times 0.42\ MeV) \\ \hline = 24.68\ MeV \end{array} $$

FIGURE 35



Steps in the proton-proton chain.

The emitted positrons annihilate upon colliding with any electrons, releasing an additional 2 × 0.511 MeV = 1.02 MeV worth of energy.

The first step in the proton-proton chain, the fusion of two protons to form a deuterium nucleus, occurs with a low enough probability that it serves as a "bottleneck" that regulates the rest of the reaction cycle. If this step happened more frequently, the Sun would have a much shorter lifetime as it more rapidly converted its supply of hydrogen into helium.

A more complex series of reactions called the carbon (or CNO) cycle serves as the primary power source of stars that are hotter and more massive than the Sun. CNO stands for carbon-nitrogen-oxygen, which are the elements that serve as intermediaries in the conversion of hydrogen to helium. No net carbon is used up in this cycle, and the overall effect is the same as the proton-proton chain.

In 1920, English physicist Arthur Eddington was the first to propose that the energy produced by stars resulted from the fusion of hydrogen to form helium. However,