17.7: Nuclear Fusion

In the discussion of nuclear binding energy, we noted that heavy elements can become more stable by splitting into smaller nuclei and releasing energy as they do so. This formed the basis for the discussion of nuclear fission. At the less massive end of the BEN curve, we see that nuclei become more stable as they increase in nucleon number. The process of combining lighter nuclei is called *nuclear fusion*. Since the BEN increases as smaller nuclei are fused together, energy is released in the process. The energy that is released can come in the form of kinetic energy, or the energy can be radiated away as a photon. The fusion process can only occur at high temperatures because the positively charged nuclei repel each other via the Coulomb force. Only atoms moving at very large speeds can come close enough for the strong force to overcome the Coulomb repulsion and cause the nuclei to merge into a single nucleus. We imagine this process to be similar to the behavior of two droplets of liquid that combine into a single drop. The edges of the droplets have to touch before surface tension can merge them.

The Solar Spectrum

Investigation of the spectrum of light emitted by the sun shows an abundance of hydrogen and helium. How this relates to the sun's energy output was not proposed until 1938, when Hans Bethe showed that solar energy is the result of hydrogen fusion in the sun's interior. This fusion process is known as the proton-proton chain and is shown by the following reactions:

$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e} + {}^{0}_{0}\,\nu_e + Q$$

$$^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma + Q$$

$$^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + Q$$

Example 17.7.1

Calculate the Q value of the final part of the proton-proton chain. Use 3.016 u for the mass of ${}^{3}_{2}\mathrm{He}$, 4.003 u for ${}^{4}_{2}\mathrm{He}$ and 1.008 u for the mass of hydrogen. Answer in units of MeV.

Solution

Again, the relevant equation is the mass-deficit equation. 2(3.016 u) - (4.003 u + 2(1.008 u)) = 1.3 x 10^{-2} u. Using the conversion factor between u and MeV gives a final value of 12.109 MeV released per fusion.

The fusion of hydrogen forms an important part of the life cycle of a star. The energy that is released in the sun's interior leads to a pressure expansion that counteracts the gravitational forces acting to compress the sun. As long as the sun has hydrogen to fuse, it can remain in a stable state. The current model has stars fusing hydrogen into helium, and once the hydrogen is most fused the star begins to fuse helium nuclei to produce heavier elements. This process is called *nucleosynthesis*. Possible reactions include the following fusion chain:

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

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

$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$$

It is believed that the carbon and oxygen nuclei that are produced in these processes migrate to the surface of the star by convection. As stars reach the end of their life cycle, they shed their outer layers and eject these heavier elements into the cosmos. Spectral analysis of nebulae show the presence of oxygen atoms, thus supporting the hypothesis. It is now believed that many of the massive nuclei found on Earth were fused in the cores of stars.

However, in order to fuse the heavier elements, larger and hotter stars are required. As the proton numbers increase it becomes increasingly difficult to overcome the Coulomb repulsion, so these atoms need to be moving at much higher speeds. If the stars are massive enough their core temperatures will be sufficiently high to produce more complex nuclei:

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{23}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}$$

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma$$

$$^{12}_{6}\mathrm{C} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{28}_{14}\mathrm{Si} + \gamma$$

Nucleosynthesis will continue until the core of the star is primarily iron and nickle. Iron is one of the most stable nuclei, so it will not be exothermic, but it will require energy in order to fuse into heavier atoms. This means that an iron core will not produce energy, so there is nothing to offset the gravitational pressure trying to collapse the star. Therefore, the star collapses into itself which causes the core temperature to spike, reaching temperatures of billions of degrees. The resulting pressure waves cause the star to explode and during this process elements heavier than iron can be formed. The resulting heavy elements are flung into space from the explosion.

Eventually, these atoms will be recycled into new stars and their accompanying planets, pulled together by the gravitational force. Images from the Hubble Space Telescope show evidence for this process in the Serpens cloud core located about 750 light years from earth, as new stars form from cooling dust and gases. These new stars will begin the nucleosynthesis process all over again. As Carl Sagan said: “The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.”

Fusion on Earth

It is the process of nucleosynthesis that scientists are trying to utilize when they design and build fusion reactors. In particular, this two-step process is thought to be the most promising for practical use:

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{1}\mathrm{H} + ^{1}_{+1}\mathrm{H}$$

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

There are still a number of technological challenges left to solve. As mentioned earlier, trying to force two positively charged objects close enough together that the strong force can cause them to attract is extremely difficult. Extremely high temperatures are needed for the nuclei to fuse, on the order of ten million Kelvin. Designing materials that can withstand these temperatures and then finding a way to harness the resulting energy are significant challenges.

The reason fusion is so appealing is that it would be the first power supply that wouldn't produce harmful combustion by-products. The result of the fusion cycle is to produce helium and an extra neutron. The neutron can be used to create more of the hydrogen isotope needed for the fusion process, and helium is not biologically damaging. Access to power without pollution will be transformative.
