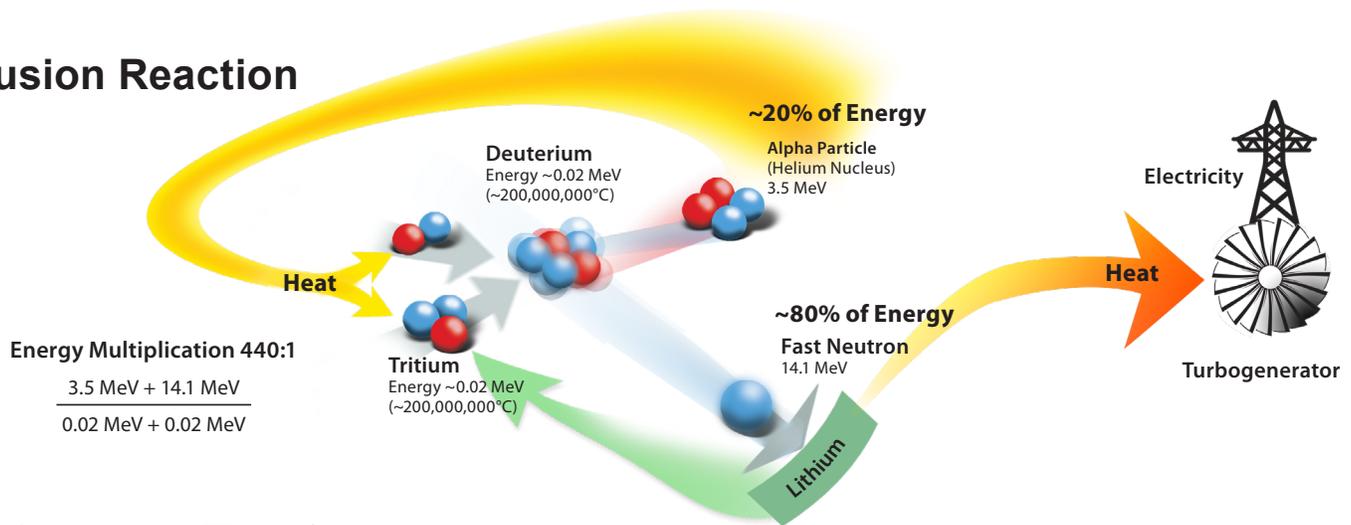


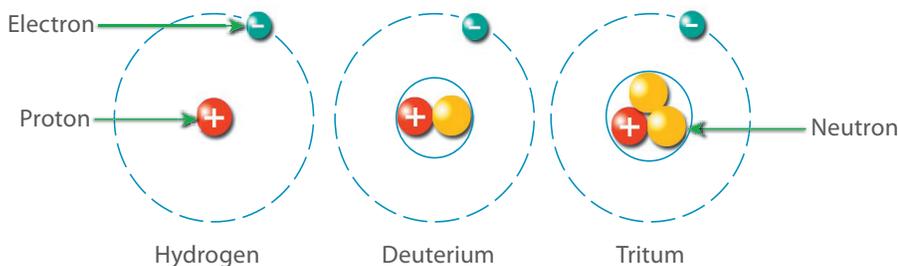
## Fusion Reaction



## About Fusion

### Fusion Basics

Throughout history, the way in which the sun and stars produce their energy remained a mystery. During the 20th century, scientists discovered that the energy is produced through the fusion of light atoms. Albert Einstein's familiar formula,  $E=mc^2$ , provided the basis for understanding that mass can be converted into energy. With fission, heavy atoms – such as uranium – can be split to release the internal energy that holds them together. With fusion, light atoms – such as those of hydrogen – can be fused or joined to produce energy.



### Atomic and Nuclear Species

An atom is the smallest portion of an element that can exist while retaining the element's characteristics. The lightest atoms are those of the element hydrogen, and the heaviest atoms occurring naturally in significant quantities are those of uranium. Every atom has an internal structure, including a central nucleus carrying nearly all the mass, surrounded by negatively charged electrons. The nucleus has a positive electrical charge that is balanced by the electrons' negative charge such that the atom as a whole is electrically neutral. All atomic nuclei contain even smaller particles called protons, and all except one form of hydrogen also contain neutrons. The protons have a positive electrical charge, and the neutrons have no charge. The protons are responsible for the charge of the nucleus. Each species is characterized by the number of protons and neutrons in the nucleus.

### Advantages of Fusion

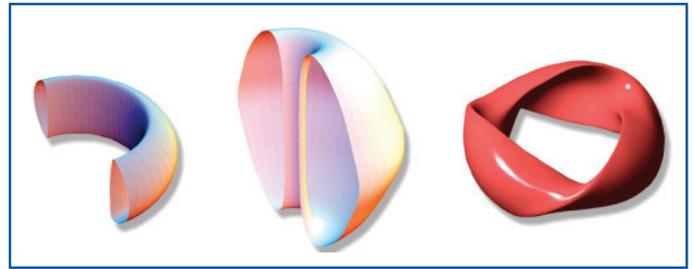
- Fusion fuel is readily available. Deuterium can be readily extracted from ordinary water. Tritium can be produced from lithium, which is available from land deposits or from sea water, by bombardment of neutrons produced by fusion. The worldwide availability of these materials would eliminate international tensions caused by fuel supply imbalances.
- The amounts of deuterium and tritium in the fusion reaction zone will be so small that a large uncontrolled release of energy would be impossible.
- Fusion energy devices produce no carbon emissions and will not contribute to concentrations of greenhouse gases.
- Any radioactive wastes generated by the fusion process will require only decades to decay. And the materials and by-products of fusion are not suitable for use in the production of nuclear weapons.

## Fusion Reactions

Many fusion reactions occur in the sun and other stars, but only a few are of practical value for potential energy production. One of these involves isotopes of hydrogen. The power production process that is most readily achievable on earth is the combination of a deuterium nucleus with one of tritium. The products are energetic helium-4, the common isotope of helium (also called an alpha particle), and a more highly energetic free neutron (n). The helium nucleus carries one-fifth of the total energy released, and the neutron carries the remaining four-fifths.

## Conditions for Fusion: Temperature and Confinement

Because nuclei carry positive charges, they normally repel one another. The higher the temperature, the faster the atoms or nuclei move. When they collide at high speeds, they overcome the repulsion of the positive charges and the nuclei fuse, releasing energy. The challenge in producing fusion energy has been to develop a device that can heat the fuel to a sufficiently high temperature and confine it for long enough so that more energy is released through fusion than is used for heating. To release energy at a level of practical use for energy production, the gaseous deuterium-tritium fuel must be heated to about 100M°C. This is more than six times hotter than the interior of the sun. These temperatures, although high, have been attained. The challenge is how to confine the deuterium and tritium for a long enough time under such extreme conditions. Part of the solution lies in the fact that, at these temperatures, all electrons of light atoms become separated from the nuclei. This process is ionization, and the positively charged nuclei are ions. The hot gas containing negatively charged free electrons and positively charged ions is known as plasma. Because of the electrical charges carried by electrons and ions, plasma can – in principle – be confined by a magnetic field. Without such a field, the plasma's charged particles move in straight lines and random directions. But in a magnetic field, the



*Many different plasma configurations have been studied. Presently, the advanced tokamak, the spherical torus, and the compact stellarator (left to right) are of greatest interest to magnetic confinement fusion research.*

charged particles in the plasma are confined and prevented from striking the walls of the vessel containing the plasma.

To produce substantial net power from fusion reactions, the following condition must be achieved: The product of the energy confinement time,  $\tau$  seconds, and the plasma density,  $n$  particles (ions or electrons) per cubic centimeter, at a temperature of 100M°C is such that  $n\tau$  must be greater than  $3 \times 10^{14} \text{ cm}^{-3} \text{ seconds}$ .

## Plasma Heating

In an operating fusion reactor, part of the energy generated will maintain the plasma temperature as fresh deuterium and tritium are introduced. However, during startup, the plasma will have to be heated to 100M°C. In present magnetic fusion experiments, insufficient fusion energy is produced to maintain the plasma temperature. Consequently, the plasma must be reheated throughout the pulse.

Because the plasma conducts electricity, it can be heated by passing a current through it – a process called ohmic (or resistive) heating. The heat generated depends on the resistance of the plasma and the current. But as the plasma temperature rises, the resistance decreases, and ohmic heating becomes less effective. To obtain extremely high temperatures, additional heating methods must be used.

Neutral-beam injection involves the introduction of high-energy atoms into the ohmically heated, magnetically confined plasma. The atoms are immediately ionized and are trapped by the magnetic field. The high-energy ions then transfer part of their energy to the plasma particles in repeated collisions, thus increasing the plasma temperature.

In radio-frequency heating, high-frequency waves are generated by transmitters outside the vacuum chamber. If the waves have a particular frequency, their energy can be transferred to the charged particles in the plasma, which collide with other plasma particles, increasing the bulk plasma temperature. Radio-frequency waves also can be used to drive the plasma current.