Nuclear Fusion

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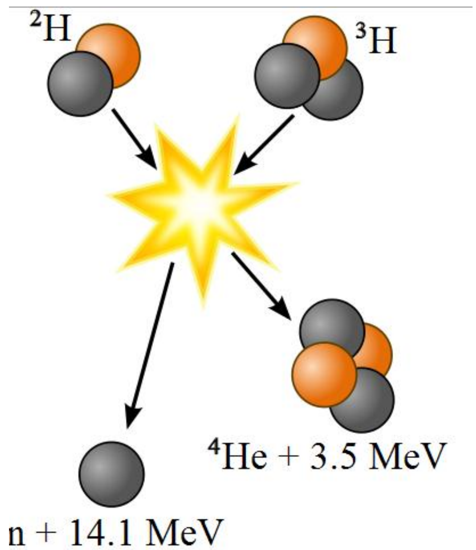
Imagine a source of virtually unlimited energy. This source of power is what makes the stars shine. It can be used to create the most powerful weapons mankind has ever known, and it may one day generate electric power for the world. This source of energy is called nuclear fusion.

Nuclear fusion is the process by which multiple atomic nuclei fuse together to form one larger nucleus [2]. In 1905, Albert Einstein worked out something interesting in his paper, *Does the Inertia of a Body Depend Upon Its Energy* [1]. He discovered that if a body gave off energy L, it's mass would diminish by L/c^2. Rearranging this and using E to represent energy gives the famous equation, $E=mc^2$. This means that energy and mass are two forms of the same thing and implies that matter can be converted into energy, and because the speed of light is so great, a small amount of matter can be converted into an enormous amount of energy. One kilogram of matter is equivalent to about 9.0×10^{16} J.

In some nuclear reactions, a small amount of matter will be converted to pure energy. Conversion of matter into energy is how all nuclear power is generated. The more familiar form of nuclear energy, which supplies about a fifth of the electricity used in the United States [3] is nuclear fission. Fission is the opposite of fusion. Large nuclei, usually Uranium-235 in industry [2], are split into smaller nuclei. However, nuclear fission of Uranium has problems. Uranium itself is a very toxic material. It is difficult and expensive to mine. Shipping and handling it puts workers in harms way. After it is used as fuel, deadly waste is leftover that can remain radioactive for centuries. Fusing together lighter elements to generate energy has none of these problems. Heavier elements of hydrogen, deuterium and tritium, can be fused into helium [4].



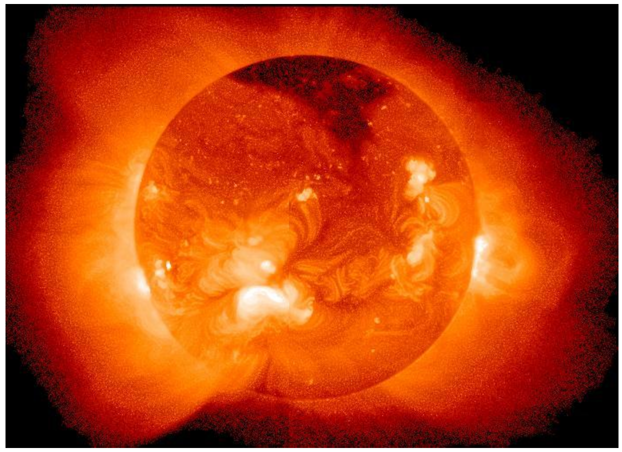
A depiction of deuterium fusing with tritium. [16]

In these reactions, more mass is converted to energy then in fission reactions, so fusion generates much more energy. The oceans are full of hydrogen atoms in water molecules. About one out of every seven thousand hydrogen atoms in nature are deuterium [5] which can be used as fuel. It is relatively easy to extract the heavy water (water with deuterium atoms) to isolate a virtually unlimited supply of the fuel. This process does not produce the radioactive materials that fission does. Any radioactive material produced by fusion is much less dangerous. While fission will produce materials that will be dangerous for centuries, the half-life of radioactive material from intermediate fuel used by fusion would be much less. There would also be no risk for a meltdown in a fusion power plant, because there would be such small amounts of fuel reacting at once [6]. This may all sound good, however, fusion has one major downside at the present time. It is very hard to start, and even more difficult to sustain.

For fusion to happen, nuclei have to be very close together. The nucleus of an atom has a positive charge, which repels other nuclei. To get them to fuse together, they must be compressed into a tiny space, and heated to tens of millions of degrees Celsius. Only in these extreme conditions do the nuclei move fast enough, and come close enough together to overcome the electric repulsion between them and allowing the strong nuclear force to take over. Once this is achieved, keeping the reaction going becomes even more difficult. The energy generated by the fusing atoms heats up the surrounding atoms. As the fuel heats up, it has a tendency to expand. A nuclear fusion generator will try to blow itself apart once it is turned on. To make a generate usable electricity by fusion, the generate would have to engineered almost perfectly to withstand this [4].

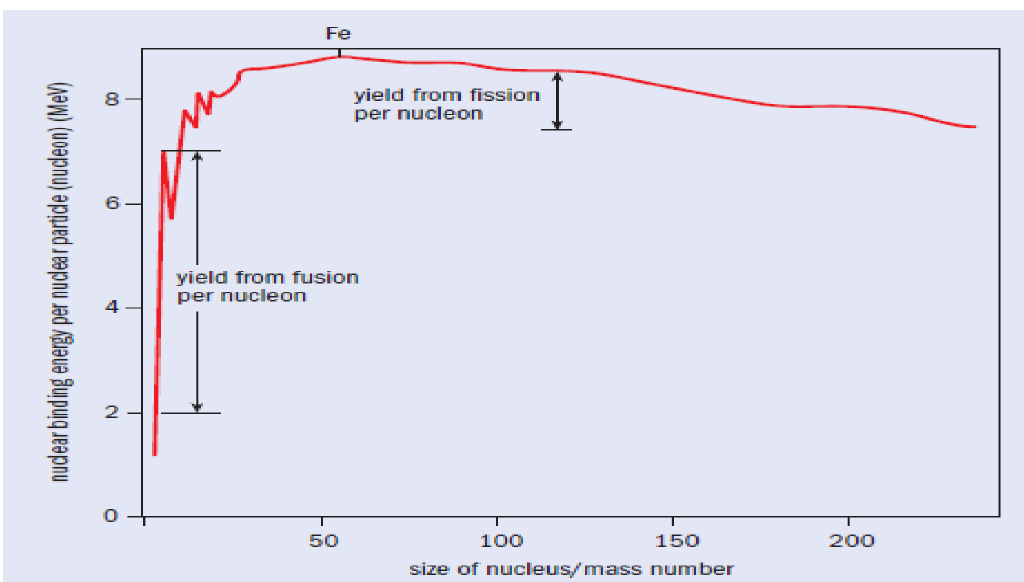
Although powering cities through nuclear fusion is something for future scientists and engineers to work out, nuclear fusion was first successfully accomplished by people in the twentieth century. On November 1, 1952, the first hydrogen bomb was detonated. The energy released completely vaporized the island of Elugelab, leaving behind a twenty mile high cloud of dust and fire. The device, called Ivy Mike, was the first test of a thermonuclear weapon [4]. Ivy Mike consisted of a nuclear fission bomb that would generate the heat required to jumpstart the fusion of deuterium and tritium. Since then, other fusion devices have been developed, including bombs, and machines using magnets or lasers to control fusion reactions. Unfortunately, a practical method of generating energy from fusion has not yet been achieved. The amount of energy generated by the fusion is comparable to the amount needed to heat the atoms to a high enough temperature to fuse while keeping them confined in a small enough space. Building and maintaining devices like this can be extremely expensive. Because of these issues, a sustainable, economic fusion generator has not yet been achieved. [7]

Despite the difficulties of achieving and maintaining fusion power on Earth, it is very common in nature. Nuclear fusion is the source of the light and heat energy generated by every star in the universe. In clouds of cosmic gas and dust in space, gravity pulls particles together in enormous amounts. If enough material is present, gravity will pull it together into stars. While it seems impossible to create the pressure and temperature required for nuclear fusion to occur here, gravity makes it happen in the cores of stars. As the matter condenses, falling inward under its own weight, the pressure and temperature rise high enough for protons to fuse together. This source of energy is what makes the stars, including the sun, shine [8]. When physicists and engineers try to generate energy through nuclear fusion, they are in essence, trying to copy the process by which stars produce energy. This paper mostly focuses on hydrogen fusion to form helium, but in reality, all elements heavier than hydrogen are formed through nuclear fusion. In the early stages of the universe, the only elements that existed were hydrogen, helium, and a small amount of lithium. Nuclear fusion inside of stars formed all of the elements up to iron. Fusing nuclei to create elements heavier than iron requires greater temperatures and pressures than those within the cores of stars. Such temperature and pressure is achieved during an event called a supernova [9]. A supernova is a an event that some large stars undergo at the end of their lives when they violently explode.



The sun is a natural fusion generator. [17]

There are two basic types of fusion. Reactions that people try to use on Earth preserve the number of protons and neutrons, while some reactions by which stars generate energy will involve and initial conversion between protons and neutrons [10]. The energy released during a nuclear reaction arises from the difference in the energy required to bind together the initial and final components.



The relationship between nucleus size and binding energy. [6]

When the energy associated with binding the initial components is greater than the energy associated with binding the products, energy will be released during the fusion. The amount of mass in the products will reflect this release of energy. If energy is released in a fusion reaction, the products will actually be lighter than the reactants. [6] It is because of this binding energy that nuclear reactions release energy in the first place. Binding energy is essentially a measure of how efficient the nucleons in a nucleus are bounded together. Consider a nucleus with Z protons and N neutrons in the nucleus. The binding energy is the energy associated with the difference of the mass of that number of protons and neutrons measured separately, and the mass of the nucleus [10]. The formula for mass energy equivalence can be used to calculate the energy released in nuclear reactions by taking into account this mass difference. The formula for binding energy is given here:

$$B = (Zm_p + Nm_n – M)c^2$$

In this equation, m_p and m_n represent the masses of the constituent nucleons. Binding energy per nucleon is at a max at the atomic weight of iron, so fusing together elements lighter than iron or splitting elements heavier than iron causes a net release in energy from the system. In fusion reactions with elements lighter than iron, the mass of the nucleus will weigh less than then that of the same number of protons and neutrons on their own. Some of the matter will have been converted to energy. Here are some examples of fusion reactions with hydrogen isotopes [7]:

$$D + D \rightarrow {}^{3}He + n + 3.25 \text{ MeV}$$

$$D + D \rightarrow T + p + 4.0 \text{ MeV}$$

$$T + D \rightarrow {}^{4}He + n + 17.6 \text{ MeV}$$

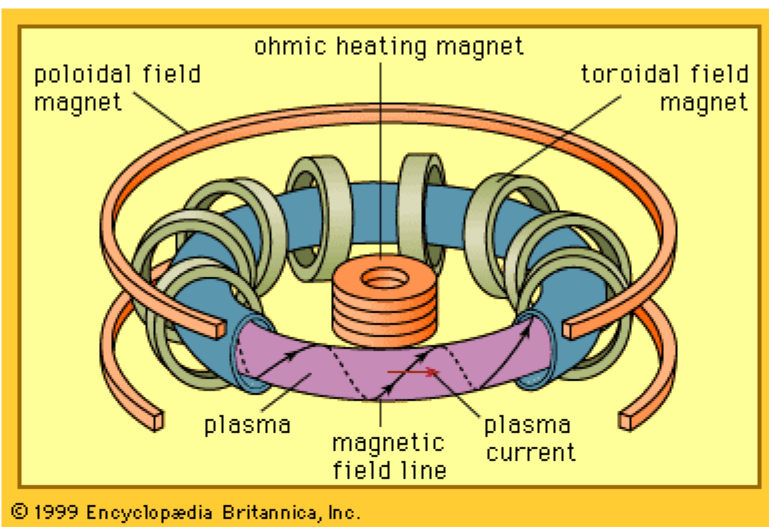
In these equations, D represents a deuterium atom, T a tritium atom, p a proton, n a neutron, and He a helium nuclei. MeV is a mega electron volt, which is a unit of energy equal to about 1.6022×10^{-13} J. The amount of energy released by burning hydrogen is about 1 eV. Gram for gram, nuclear fusion reactions generate millions of times more energy than chemical fuels.

The fusion reactions given above are the ones that might be used to generate electrical energy in the future. The fusion of the most common isotope of hydrogen, protium, has never been required even greater heat and pressure than the heavier hydrogen isotopes. Fusion of protium is only known to happen in stars. The sun fuses two protium atoms into deuterium. One of the protons in this reaction separates into a neutron, positron, and neutrino. The deuterium then fuses with another protium to form a helium-3 nuclei, and release a photon. Two helium-3 nucleus will fuse to form a helium-4 nucleus and two protons. In this three step process, the sun converts hydrogen into helium and releases energy in the form of light and heat.

Fusion only occurs when the nucleons become close enough together for the strong nuclear for to have an effect. A helpful way of thinking about this is to compare the strong nuclear force to the force between magnets. If you have two magnets far enough apart, there is virtually no force between them. However, if you move the opposite ends of the magnets close together, they will quickly snap together. If the magnets are powerful enough, they can collide violently, releasing energy in the form of heat and sound. Something similar happens with the strong nuclear force in fusion reactions. Protons will usually repel each other, but when forced close enough together under extreme conditions, the strong force takes over and pulls the protons together, securing them and releasing vast amounts of energy. [8] The strong force is 137 times stronger than the magnetic force, and will release much more energy than the colliding magnets. The range at which the strong force has an effect enough to bind nucleons together is about one to three femtometers (A femtometers is 10^{-15} meters).

There are a few ways in which people have tried to harvest fusion power. There are two convention ways to cause fusion reactions. One of them is to use to use magnetic confinement approaches. The other is called inertial confinement approaches. In magnetic confinement, powerful magnetic fields hold plasma together while high temperatures cause the nuclei to collide and have the necessary collisions. This is the most common method. The other relies on very quickly applying great force to the fuel source to cause a short fusion pulse. This is usually done with high powered lasers. [6]

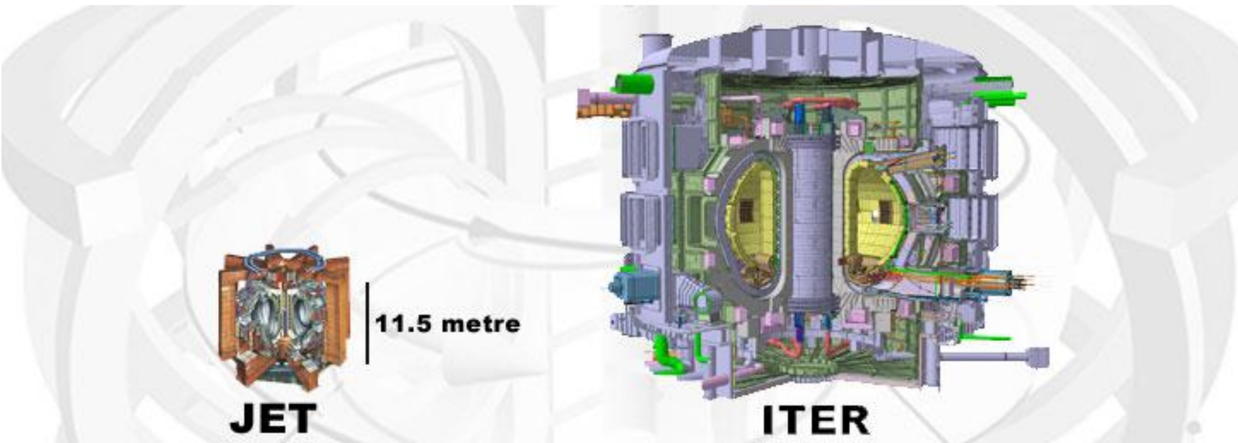
The Tokamak Fusion Test Reactor is an example of using magnetic confinement to cause fusion. It was operated at the Princeton Plasma Physics Laboratory from 1982 until 1997. It could generate temperatures up to 510 million degrees centigrade. The device used very powerful magnetic fields to control a very hot plasma consisting of a mix of deuterium and tritium. It generated enough power to supply electricity to a few thousand homes.



A visualization of the plasma in a tokamak reacor being held by magnetic fields. [10]

In a reaction taking place like the one in a tokamak reactor, the energy released will be released as kinetic energies in the resulting particles. When deuterium and tritium react, they release a helium nucleus and a free neutron. The particles will take up a fraction of the energy inversely proportional to their own mass. In this case, the neutron will take four-fifths of the kinetic energy and the helium nucleus will take a fifth of it. Neutrons are neutrally charged particles and therefore are unaffected by the magnetic field. The neutrons pass through the outer edge of the reactor and enter a region called “the blanket”. The blanket is made of materials designed to slow down the fast moving neutrons and convert the kinetic energy to heat. The heat is used to heat water or helium to produce a high pressured gas to spin a turbine and generate electricity. This is the same way burning coal generates electricity, but much more efficient and powerful. Some designs can include lithium in the blanket, which reacts with the free neutrons to create tritium, one of the fuels used in the reaction, so a nuclear generator using this method can generate some of its own fuel. The charged helium nucleus becomes trapped in the magnetic field. Its energy can help maintain the high temperature needed to sustain the reaction. Unfortunately, this creates a problem. The helium nuclei will transfer their energy to the plasma and become an inhibitor to the reaction by cooling it down. Nuclear fusion reactors must incorporate systems to remove this helium. [6]

The JET (Joint European Torus) is the largest fusion reactor in the world and the only operational fusion reactor capable of producing fusion energy at the this time. Although it produces massive quantities of energy, it consumes even more. JET is purely a science experiment. In order to better demonstrate the feasibility of fusion power, a successor to JET is now being build and scheduled to be completed in 2019. The successor is called ITER (International Thermonuclear Experimental Reactor). ITER is designed to output 500 megawatts of power for every 50 megawatts it consumes, or ten times the power put in. No fusion reactor has yet been able to yield more energy than it uses. If successful, ITER will prove nuclear fusion can be a real energy source. ITER will still be experimental and there will be no attempt to use it as a power station. Its purpose will be to pave the way for future nuclear fusion reactors later on. [12][6]



The JET and the planned ITER. [12]

It has been suggested that under certain circumstances, fusion can occur at room temperatures in a process called “cold fusion”. Cold fusion is not much of a scientific concept and is poorly defined. If an electron in a DD or DT molecule was replaced with a muon, a more massive particle, the nuclei would be forced closer together allowing a possibility of fusion. In experiments performed in the late 1980s involving the electrolysis of heavy water, excess heat and tritium seemed to be produced. The experimenters in this case argued that they had discovered a new means of causing fusion. If they had, the implications would be fantastic! Energy from fusion could be generated without having to sustain the high temperatures and pressures required for thermonuclear fusion. However, almost all attempts to repeat their experiment were failures while thermonuclear fusion has been repeatedly shown to work. At the moment, cold fusion is not science, but science fiction and wishful thinking. [13][14]

In conclusion, nuclear fusion is a very interesting process. It leads to nucleosynthesis and is responsible for the existence of most of the elements of the periodic table, generates light and heat in the cores of stars, can be used to build hydrogen bombs with incredible destructive power, and may one day provide virtually limitless electrical power to the world. However, it is not yet useful as a power source. As wonderful as it would be to have nuclear fusion power plants running cities and nations, the technology to achieve this is still out of reach, despite decades of trying. One physicist described nuclear fusion as “the technology that is always thirty years away.” [15]

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