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The Energy of the Future? A Study of Fusion

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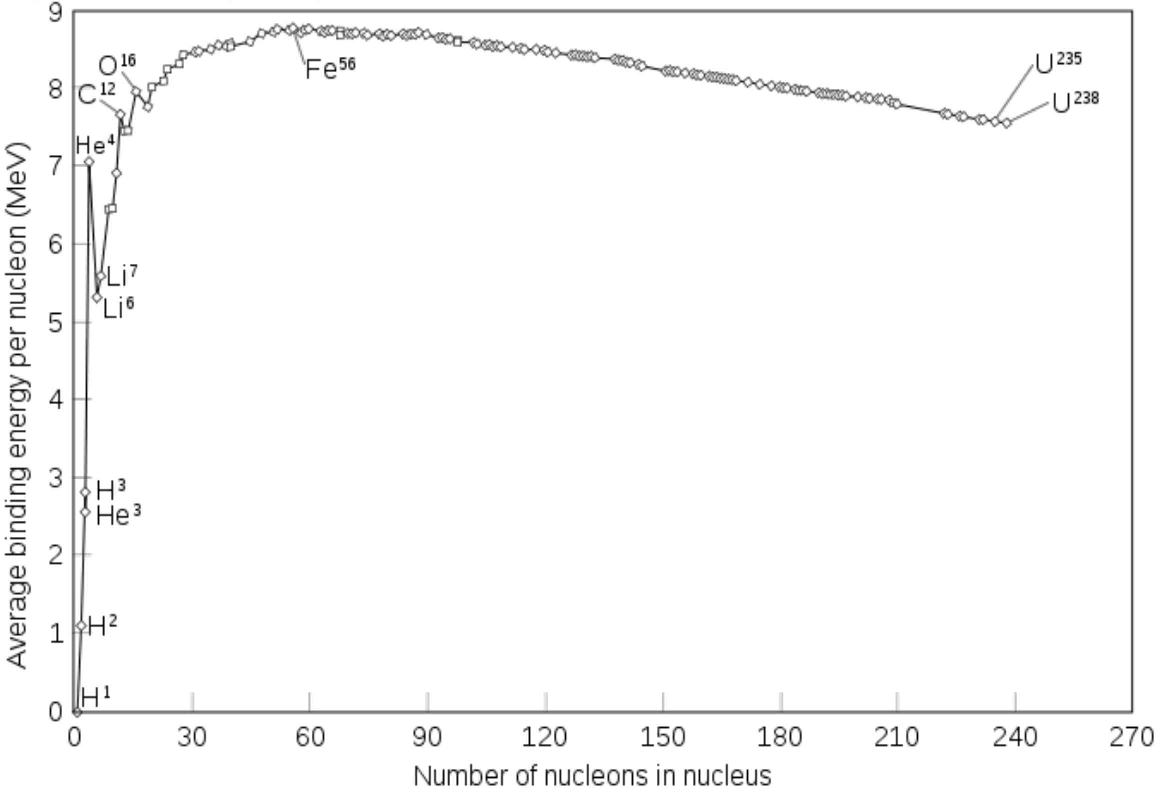
Since the beginning of time, we, as a human race, have wondered how we came to be. Eventually we discovered that this world is surrounded by other planets, that we are all orbiting around a sun, creating a solar system, which is only one of many in our galaxy, which is in turn only one of many in our universe. This raises the question of how the universe came to be. In more recent years, energy has been a buzzword. As fossil fuel levels are depleted, prices rise, and scientists begin exploring other methods of providing energy very quickly. While we still do not know exactly how we, or the universe as a whole, came to be or exactly how to solve the energy crisis, they have the potential to have the same answer: fusion.

The question now becomes, what is fusion? Fusion is the joining of two small nuclei to form a heavier nucleus. This process results in the release of large amounts of energy, and is the method of energy production in the stars. This is partially explained by Figure 1 below. As nuclei come into contact with each other, the strong force of the nuclei pull each other in, resulting in an excited state. This excited state releases energy, in this case by releasing an energized proton or neutron (Energy 2012). This is easily explained using Einstein's famous equation,

$$E = mc^2,$$

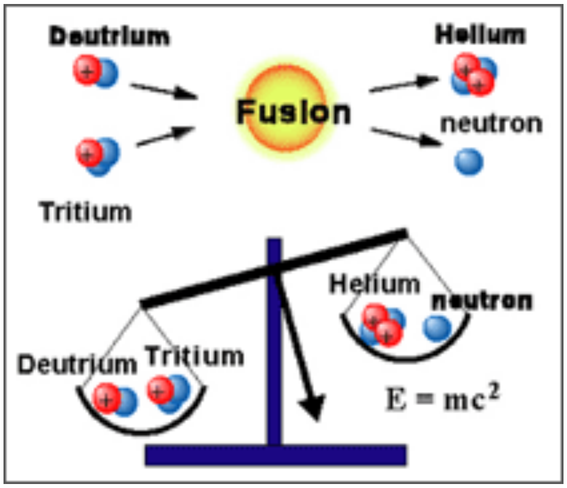
with E being energy, m being mass and c the speed of light. If Deuteron is fused with Tritium, the products, Helium and an excess neutron, have less mass. Since energy must be conserved, this means that some amount of energy must have been released during the bonding process (Ministry of Foreign Affairs of Japan 2012). Figure 2 below displays this.

Figure 1: Binding Energies of the Elements



(Energy Bulletin 2012)

Figure 2: A Fusion Reaction



(Ministry of Foreign Affairs of Japan 2012)

Atoms are constantly packed together, so why doesn't this happen more often? At normal temperatures, the Coulomb force F_c,

$$F_c = \left|\frac{kq_1q_2}{d^2}\right|$$

acting between atoms prevents such an event, with k being the Proportionality Constant, q_1 is the charge of atom one, q_2 is the charge of atom two, and d is the distance between the atoms. Obviously, the Coulomb force is weaker for greater distances between the charges. However, if the distance is too severe, the atoms will not be able to make contact and fuse. Each element has an associated cross section. If atoms come within this distance, some type of event will likely occur. Because this distance differs between atoms, it can be used to approximate which fusion reactions will actually take place. This can be used to help understand the fusion reactions given certain fuels, and why one fuel is almost completely burned up before the next begins, as explained later. The cross section is directly proportional to the energy levels. The higher the energy, the larger the cross section. This is partially because the cross section is inversely related to the Coulomb force of the atoms. The higher the Coulomb force, the smaller the cross section, because the more inward force must be exerted to interact with the atoms. As the energy levels increase, they can exert a greater force on each other, allowing the atoms to get closer together. To completely overcome the Coulomb force, the potentially colliding nuclei, the fuel, need to be at high densities and at high energy levels, equated to high temperature levels (Jelley 1990). These temperatures, in the vicinity of 10^8 or 10^9 K, have the ability to disassociate electrons and nuclei, creating plasma. This provides the nuclei with enough force to counteract the Coulomb force, enlarging the cross section and enabling the possibility for an event to take place. When the bare nuclei collide, a larger nucleus is produced and a proton or neutron is released, carrying the majority of the energy of the reaction.

The energy produced is the key. Fusion produces much more energy than fission, and has much less radioactive waste. There are several potential reactions that could be utilized:

$$D + D \rightarrow (T + 1.01\ Mev) + (p + 3.03\ Mev)$$

$$D + D \rightarrow (He^3 + 0.82\ Mev) + (n + 2.45\ Mev)$$

$$D + T \rightarrow (He^4 + 3.52\ Mev) + (n + 14.06\ Mev)$$

$$D + He^3 \rightarrow (He^4 + 3.67\ Mev) + (p + 14.67\ Mev).$$

D is Deuterium, *T* is Tritium, *n* is neutron, *p* is proton, helium ions are represented by *He* and their corresponding atomic mass, and *ev* is electron volts, the unit for kinetic energy divided by the charge of a proton. The initial fuel would need to be added, however, once the reactions began, the products from the reactions would be utilized as fuel for subsequent reactions (Rose 1961). It is obvious based on the energy released that the more favorable reactions from an energy standpoint would be the second two. The first two do not produce as much energy as would be liked, and while it is not obvious, they have much smaller reaction cross sections, making them less likely to react at a set temperature. With increased temperatures, their cross sections would be enlarged, making their fusion more likely. Looking at the second two, the energy released is pretty similar. However, because of the size of the cross section for the D-T reaction, it is the most likely to occur, making it the most favorable reaction to use in a commercial setting. Hypothetically, the best case scenario would be to start with a D-D reaction. If it could be controlled long enough, its products would then become the reactants of a D-T or D-He^3. The outcome would be the total energies of all of the reactions, $D + D \rightarrow D + T \rightarrow He^4 + 21.62\ Mev$ or $D + D \rightarrow D + He^3 \rightarrow He^4 + 21.61\ Mev$. It is interesting to note that the two reactions, while they have different intermediate reactions, end with the same products, $He^4 + p + n + \approx 21.61\ Mev$.

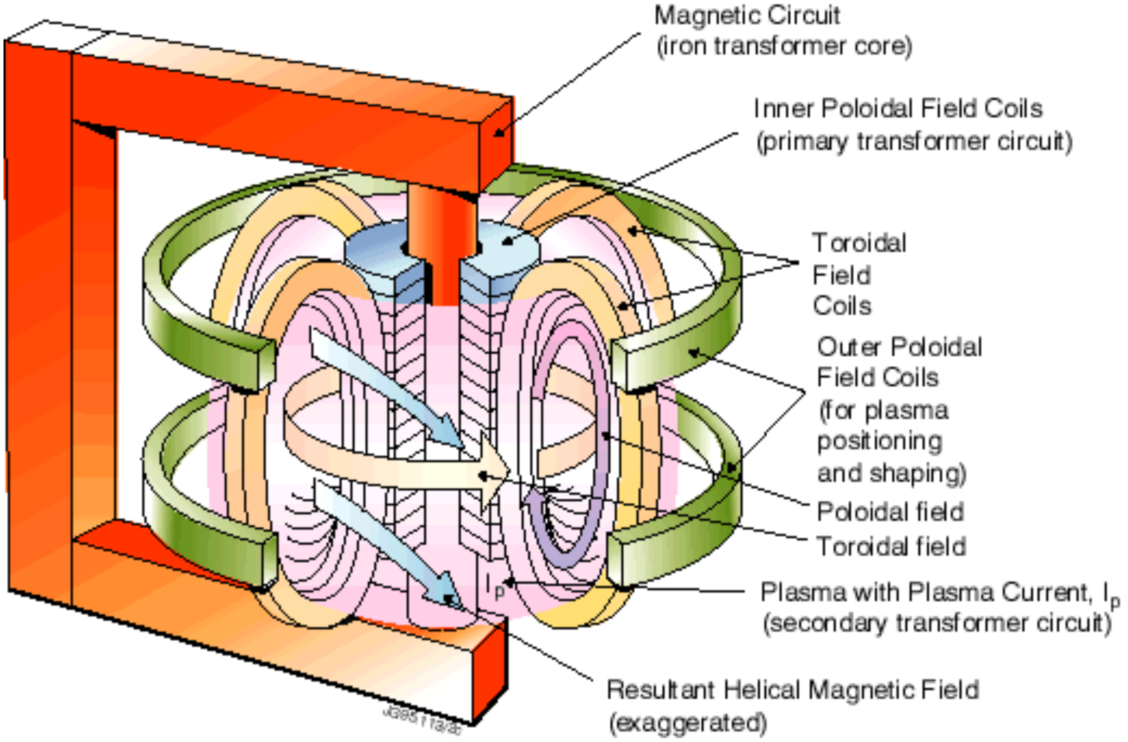
There are obviously problems with using fusion in a commercial setting. The operation temperature, being at multiple orders of ten Kelvin, are much too high to be confined with any material we have on hand. However, the particles are all charged, making it theoretically possible to use electromagnetic fields to confine the plasma, keeping it away from material walls. But confining it at all poses its own problems. The material walls would actually act to cool the plasma, making reactions less favorable. Luckily, many collision factors outlined by Rose drop off significantly in importance as the energy levels increase. Meaning elastic scattering, charge transfer, excitation energies, ionization, electron attachment, recombination, and secondary emission are of little to no importance, because the energy levels are so high. However, sputtering, the process by which "Ions of the gas strike surfaces and eject atoms of the surface material, which deposit elsewhere. (Rose 1961)" is of great consequence.

With these considerations in mind, a discussion on commercial fusion may commence. The initial question is how to harness the energy released in fusion. As discussed earlier, the fusion reaction D-T is the best fit for commercial production. Unfortunately, Tritium is not a naturally occurring element. However, a blanket is necessary to capture the high energy neutrons in a D-T reaction. Because the capture cross section is so large for the neutrons, the blanket can be relatively thin, while not sacrificing usefulness. Using a Lithium blanket around the fusion reactor simplifies the matter,

$$Li^6 + n \rightarrow \mathrm{T} + He^4 + 4.8\ Mev,$$

thus capturing the neutrons as well as producing the fuel for the reaction. The only way to capture the energy is through heat. The blanket would be heated by the energy deposited by the neutrons. This heat could then be harvested by using it to heat water pipes, creating steam, which would be used to rotate turbines, generating power, like any good hydrothermal process (Jelley 1990). Another consideration must be the air quality inside the reactor. To maximize the efficiency of the fusion reaction, it is desirable to keep any impurities from the fuel. This includes air molecules. Therefore, the wall surrounding the reactor must be in excellent shape. Air molecules have the ability to seep through small spaces. If the vacuum wall is not in great shape, the entire reactor has problems. It must also be able to withstand extreme heat. One issue mentioned earlier was sputtering, gas ions striking a surface and chipping off a piece of it. The vacuum wall must be impenetrable, even when high velocity, high energy ions strike it at a compromising angle. Plasma, being at such high temperatures, has the ability to severely damage surfaces and structures. To prevent the plasma from excessive contact with the vacuum walls, coils may be used to produce an induced current. In the best case scenario, superconducting coils will be placed outside a cylinder with an opening for the insertion of reaction fuel. This minimizes the energy input when compared to running the coils inside the cylinder, among the plasma- the resistivity increases with increased temperature (Rose 1961). For a coil placed outside the cylinder, the structure is that of a solenoid. Alternately, a cylinder can be bent in a torodial shape and utilized as the secondary of a transformer with one turn. When a pulse from a capacitance bank is run through the primary, the square connector has a current, *I*, run through it. This current induces a current in the torodial. Using specializations of Amperes Law and other Maxwell equations specific for a torodial geometry, the plasma will be centered in the torodial cylinder and flowing in a direction that can be found using the right hand rule. A successful method was utilized in 1997 using a Tokamak reactor, such as the one in Figure 2.

Figure 2: Tokamak Reactor



(Splung.com 2012)

The Tokamak reactor successfully held a fusion reaction. It only produced about 65 percent of the initial energy, but it proves that fusion reactions have the potential to be a viable energy source for some date in the future. This model uses a magnetic field to keep the plasma moving and confined, as opposed to using a solid surface. Further experimentation is necessary to make this more efficient. The reaction will need to be held for longer, allowing more time for fusion reactions to take place, increasing the amount of energy output per unit fuel (Willis 1999).

With this knowledge of nuclear Physics, the Big Bang Theory can be explained, at least in part. A super dense blob of matter exploded. Because it was so dense and compact, the temperature was very high. The force of the explosion caused the matter to spread out, while the gravitational force every object exerts diminished the expansion in part. The Law of Conservation of Mass states that matter can neither be created nor destroyed. So how did all we see come to be? The part concerned with nuclear physics and fusion helps explain this, beginning after the initial matter has exploded, and is in the process of distribution across free space. This matter consists of the building blocks of the universe: neutrons, protons, and electrons. At extremely high temperatures, such as $6 * 10^9$ K or above, neutrons will experience Beta decay into protons, electrons, and anti-neutrino, according to:

$$n \rightarrow p + e^- + \overline{v_e}.$$

At the same time, electrons will capture and bond with protons to form neutrons:

$$e^- + p \rightarrow n + v_e.$$

These processes initially balance each other out; however, as the matter expands and cools to around $1 * 10^{10}$ K, electron capture slows while Beta decay continues. The neutrons are only stable at this temperature, and therefore Beta decay is prevented, only if the neutrons bond with a proton, forming deuteron, an isotope of hydrogen. However, at high temperatures, deuteron does not exist long enough to bond with another proton to form larger nuclei. As the universe continues to expand and therefore cool, the deuteron is able to capture a proton to produce ^{3}He, which can then attract a neutron to form ^{4}He. Around this time Beta decay also slows. However, to form new species of nuclei, either free neutrons are needed, or the protons and electrons must react. Because the matter is unevenly distributed in the initial explosion, clusters are able to attract each other with gravitational force, forming stars. The heat produced as the density of the star increases is sufficient to begin burning the hydrogen, and fusion takes place. As the process continues, the temperature rises and energy is produced. Because of the intense heat, thermal pressure is present, counteracting the inward force of the gravity, preventing the star from collapsing in on itself. While there are several different options for the atoms to interact, at this phase they all end in the production of ^{4}He. Because the energy required to burn ^{4}He is so much higher than that to burn hydrogen, all the hydrogen is burned up before the helium begins to burn. Eventually, depending on the initial mass of the star, the hydrogen is burned up in the core of the star, causing the inside to cool. This lessens the thermal pressure, allowing gravitational force to contract the star. As the density of the core increases, so does the temperature. At a certain temperature, the star can begin to burn the build up helium in fusion reactions as well. The outer edge of the star is a different story. Because the outer surface has a lower temperature than the core, the fusion reaction converting hydrogen to helium takes more time. This results in the outer edge still burning hydrogen, while the higher temperature in the core allows for the fusion of helium.

Hydrogen burns at a lower temperature than helium, resulting in a reddish hew to the outside of the star, while the inside is significantly more hot. In time, the core will again run out of fuel, allowing the star to condense, raising the internal temperature enough to burn successively heavier elements, such as carbon, oxygen, neon, and silicon, while around the edges the slower, lower temperature reactions are still taking place. The resulting composition of the star is much like a cut out of a Gobstopper, each ring having a higher temperature and therefore a different color the closer it is to the center. This process, while described simply and very bluntly, can take billions of years. However, it must eventually end. Fusion only works for smaller masses- the more protons in the nucleus, the higher the Coulomb force and the less the binding energy, inhibiting the collision and bonding of the nuclei. Therefore, once the star has burned up to roughly Barium, fusion no longer takes place. If the star has enough mass, the gravitational force will be sufficient to cause it to contract, and eventually explode. This creates a very high energy environment, allowing heavier atoms to be created, and the mass of the star to be spread out over the universe (Wong 1998).

We do not have all the answers. Will we one day be able to know how the universe began? Will we one day have the materials and technology to harness the mighty power of fusion? We may not know now, but with further research and technological advances, one day we may find the answer to our questions.

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