How Is Nuclear Fusion Going?

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Math 190S

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1.Introduction

In nuclear physics, nuclear fusion is a reaction in which two or more atomic nuclei come close enough to form one or more different atomic nuclei and subatomic particles like neutrons or protons. The difference in mass between the products and reactants is manifested as the release of large amounts of energy. [1]

For example: two small atoms, for example, deuterium and tritium, under certain conditions (e.g., ultra-high pressure), will have nucleus polymerization, which produces neutrons and helium - 4, and accompanied by large energy release.

Research into developing controlled thermonuclear fusion for civil purposes initially began in earnest in the 1950s, and it continues to today. It seems a perfect way to solve the energy shortage if devices that can take advantage of the energy released by the nuclear fusion are designed and applied to real world because compared with a conventional (carbon) combustion process the energy gain is greater by six orders of magnitude!

2.Basic Principle

2.1 Mass turning into energy

According to our understanding of modern physics, matter is made of atoms [2]. Their constituents are positively charged nuclei surrounded by negatively charged electrons. Two light nuclei, when they approach each other, undergo, with a certain probability depending on their separation, a fusion reaction. Energy is gained in the process, which is carried away as kinetic energy by the helium atom and the neutron. At the same time, mass is lost: the combined mass of the products is lower than that of the reactants. (Figure 1) [3]

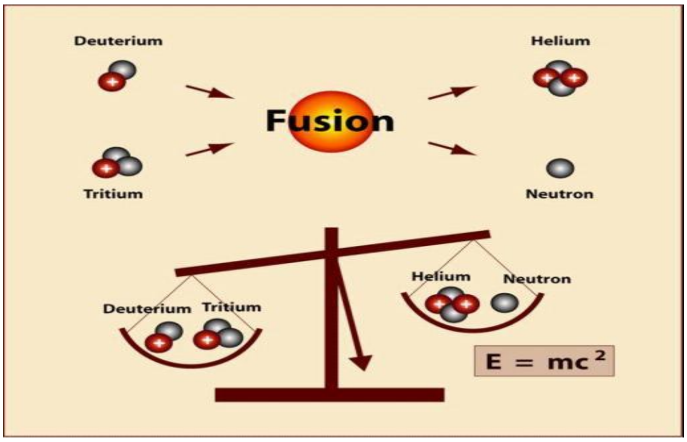

Figure 1

With the mass-energy equation：

$$E = mc^2$$

we can figure out that the loss in mass is converted to the energy and then released.

2.2 Requirements for fusion

The nucleus is positively charged, so coulomb force can block the nucleus from getting together. A large amount of energy will be consumed to overcome coulomb barrier. Light cores have less charge; thus, they need to overcome much smaller barrier when they fuse, and the more energy is released. (Figure 2)

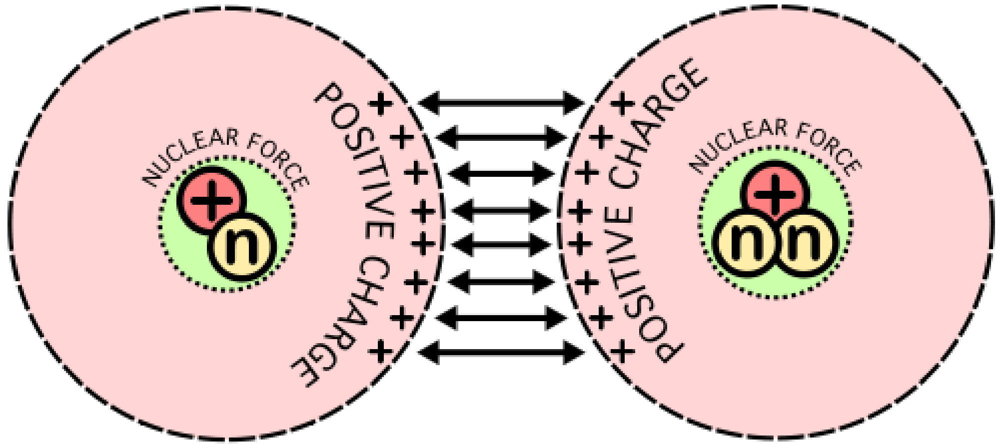

Figure 2

With the increase of atomic nuclei to a point, the potential energy needed to overcome the fusion reaction is greater than the energy produced by the reaction, namely there is no net energy produced. This critical point is the iron 56. (Figure 3)

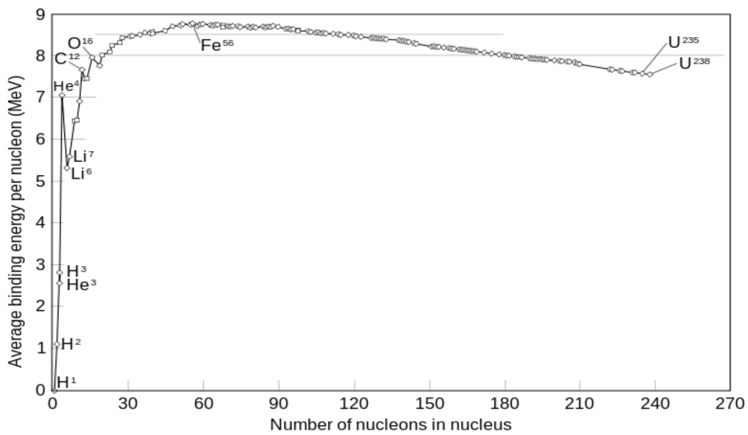

Figure 3

The deuteron and tritium nuclei are the best fuels for nuclear fusion. Because for neutrons that are relatively higher than protons, their barrier is smaller. An electrically neutral neutron uses nuclear force to tightly bind the nuclei. The binding energy of neutrons and protons of the tritium nucleus are the highest among the stable nucleus, with two neutrons and one proton. Increasing the proton or reducing the neutrons will make it more demanding for energy to overcome the barrier. (Figure 4) [4]

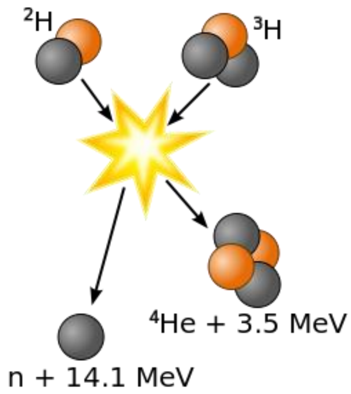

Figure 4: Schematic of the fusion reaction in which deuterium and tritium form a helium atom and a neutron. Mass is lost in the reaction and energy gained.

Under normal conditions nuclei are separated at least by the so-called atomic radius which reflects the presence of the surrounding electron cloud. Under these conditions fusion does not take place. Since only when the distance between the nuclei is less than 10fm could the nucleus has a nuclear force, the nucleus must be aggregated by external energy. Even at a very hot, dense center of the sun, one proton has to wait billions of years on average to get involved in a fusion. To make fusion actually be applied to production, the utilization of the nucleus must be critically increased: the temperature must increase to 10^8K, or the maximum pressure have to be applied. [5]

3.Source For fusion

One of the main motivations for fusion research has been that fusion was considered as a practically unlimited source of energy. The argument is based on the abundance of the fusion fuels - lithium and deuterium - and the very small quantities required. A 1 GWe fusion power plant would require annually 110 kg deuterium and 380 kg lithium consumption. []

Deuterium is a hydrogen isotope. In terrestrial hydrogen sources, such as sea water, deuterium makes up one part in 6700. Given the above annual consumption rates it can be shown that fusion could continue to supply energy for many millions of years. The oceans have a total mass of 1.4 * 1021 kg and therefore contain 4.6 * 1016 kg of deuterium; moreover, there is already a mature technology for extracting the deuterium. [6] One of the main applications is the production of heavy water for heavy water-moderated fission reactors. Existing plants can produce up to 250 t/a of heavy water which means a production of 50 t/a of deuterium. This would be enough to supply deuterium for 500 fusion plants each with 1 GWe capacity. Obviously, deuterium supply places no burden on the extensive use of fusion. What about tritium? As we have mentioned above, tritium, also a hydrogen isotope, will be bred from lithium using the high flux of fusion neutrons. Lithium is found in nature in two different isotopes $^{6}_{3}\mathrm{Li}$ (7.4 %) and $^{7}_{3}\mathrm{Li}$ (92.6 %). The two nuclear reactions

$$^{6}_{3}\mathrm{Li} + \mathrm{n} -> \mathrm{T} + {}^{4}_{2}\mathrm{He} + 4.8\ \mathrm{MeV}$$

$$^{7}_{3}\mathrm{Li} + \mathrm{n} -> \mathrm{T} + {}^{4}_{2}\mathrm{He} + \mathrm{n} - 2.5\ \mathrm{MeV}$$

are relevant Since the second reaction is endothermic only neutrons with an energy higher than the threshold can initiate this process. In most blanket concepts, the reaction with 6Li dominates, but in order to reach a breeding ratio exceeding unity the $^{7}_{3}\mathrm{Li}$ content might be essential. [7]

Lithium can be found in:

- salt brines, in concentrations ranging from 0.015 % to 0.2 %
- minerals like spodumene, petalite, eucryptite, amblygonite, lepidolite which the concentration varies between 0.6 % and 2.1 %.
- sea water; the concentration of Li^{+} in sea water is 0.173 mg/l

4.The application of nuclear fusion

4.1 Fusion in the sun

The most important fusion process in the universe is the one that powers stars including Sun. In the 20th century, it was realized that the energy released from nuclear fusion reactions accounted for the longevity of the Sun and other stars as a source of heat and light. [8] The prime energy producer in the Sun is the fusion of hydrogen to form helium, which occurs at a solar-core temperature of 14 million kelvin. The net result is the fusion of four protons into one alpha particle, with the release of two positrons, two neutrinos (which changes two of the protons into neutrons), and energy. [9] For different stars of various mass, different reaction chains are involved. For stars the size of the sun or smaller, the proton-

proton chain dominates. (Figure 5)

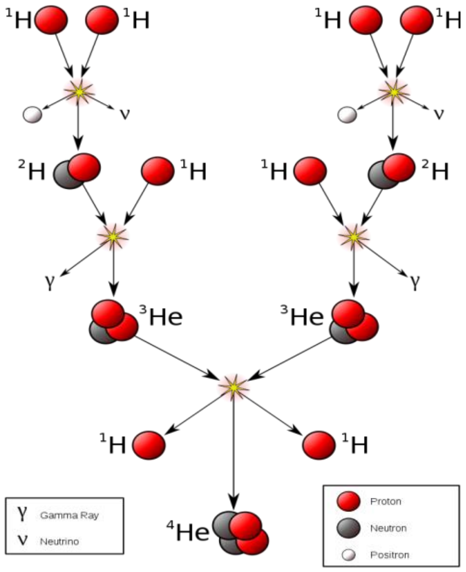

Figure 5

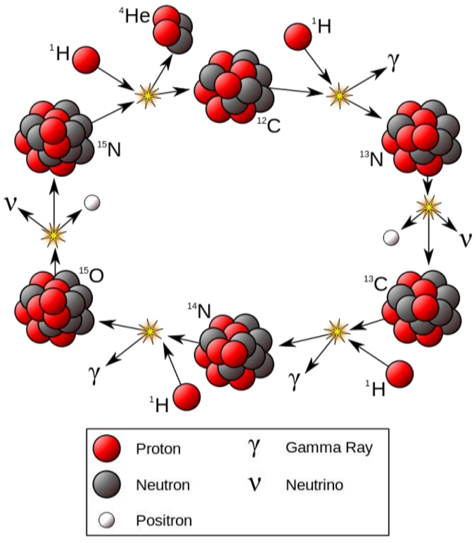

Figure 6

In heavier stars, the CNO cycle is more important. (Figure 6)

As a star uses up a substantial fraction of its hydrogen, it begins to synthesize heavier elements. However, the heaviest elements are synthesized by fusion that occurs as a more massive star undergoes a violent supernova at the end of its life, a process known as supernova nucleosynthesis. [10]

4.2 Controlled fusion by human----Status of Fusion Research

4.2.1 Development of fusion technology

Fusion gives rise to complex technologies and still demands progress in various fields such as superconducting magnets, high heat load materials, materials able to withstand high neutron flux, remote handling devices and plasma heating techniques.

Now humans have been able to achieve uncontrolled nuclear fusion, such as hydrogen bombs; It can also trigger the controlled nuclear fusion, but the input energy is greater than the output, and the reaction time is extremely short. [] To make the energy utilized by human effectively, control of reaction speed and temperature must be achieved and the energy put-out must be continuous and stable. Triggering the fusion reaction needs energy (about 100 million degrees), so the energy produced by artificial fusion can have an economic effect only when the energy that triggers the fusion reaches a certain ratio with the energy put-in. Scientists are trying to figure out how to control nuclear fusion, but there's still a long way to go.

In 2005, some scientists believed they had successfully made small nuclear fusion devices, and had been preliminarily verified. The first experimental fusion power station would be based in France.

Based on February 12, 2014, research teams of the British scientific journal nature, the U.S. department of energy's National research institute at the National Laboratory Moore Lawrence (English: Lawrence Livermore National Laboratory) confirmed that when using ultra-intensity laser to implement nuclear fusion experiments, the energy released from fuel exceeds the input of energy for the first time. [11]

Now the construction of the world's biggest experimental tokamak reactor （）、、 for the international thermonuclear experimental reactor has begun in the south of France. At present, many tokamak devices can produce nuclear fusion, but only a after short moment, must they be closed to avoid destruction. So, there is only experimental research value by now but no practical use. The lining material is the key to whether tokamak has practical value, which becomes a focus of research in countries around the world.

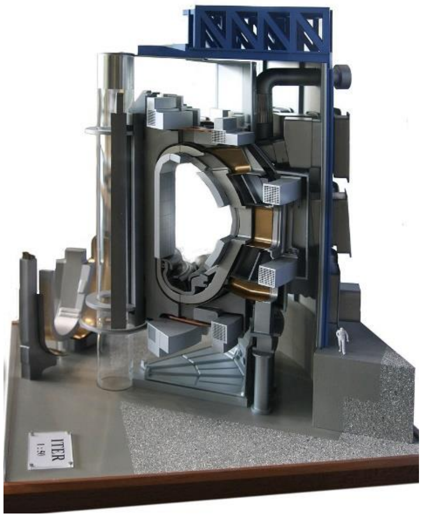

Figure 7: The tokamak device of D ring is the most promising controlled fusion design

4.2.2 Methods for achieving fusion

4.2.2.1 Thermonuclear fusion

The energy generation rate in the core of a star balances the gravitational force of the material in the star. A more massive star generates more energy, thereby holding itself up.

The energy generation rate depends on the temperature and density in the region where fusion occurs. Where the temperature and density are higher, fusion proceeds more furiously, both because the colliding nuclei are moving faster and because the higher density increases the likelihood that a collision will occur.

(Figure 8)

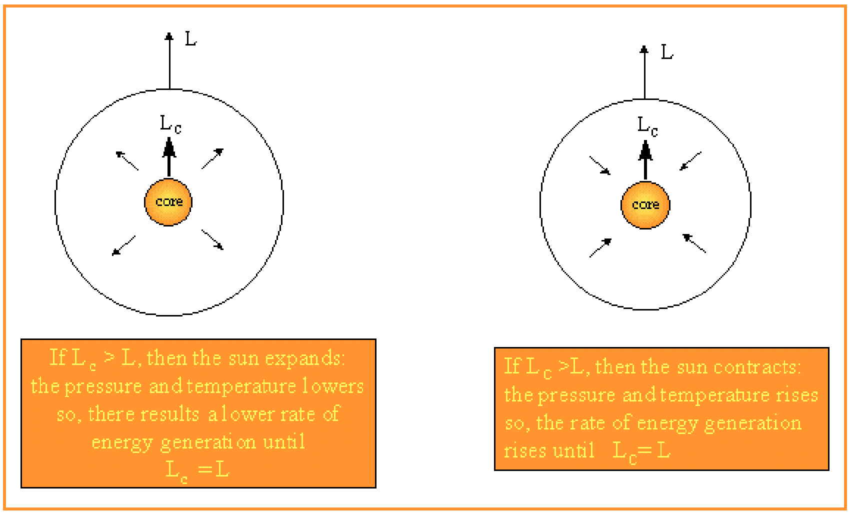

Figure 8

If the energy generation rate is too high, then the luminosity produced in the core L_c is too great, and the core expands, subsequently cooling, and thus restoring the proper rate of energy production.

Likewise, if the energy generation rate is too low, then not enough luminosity is produced to balance the inward pull of gravity. Therefore, the core contracts, thereby heating up so that the reaction rate is restored to its equilibrium level. [12]

4.2.2.2 Inertial electrostatic confinement

For every volt that an ion is accelerated across, its kinetic energy gain corresponds to increase of temperature of 11,604 kelvins. For example, a typical magnetic confinement fusion plasma is 15 keV, or 170 megakelvin. An ion with a charge of one can reach this temperature by being accelerated across a 15,000 V drop. In fusors, the voltage drop is made with a wire cage. However high conduction losses occur in fusors because most ions fall into the cage before fusion can occur. This prevents current fusors from ever producing net power.

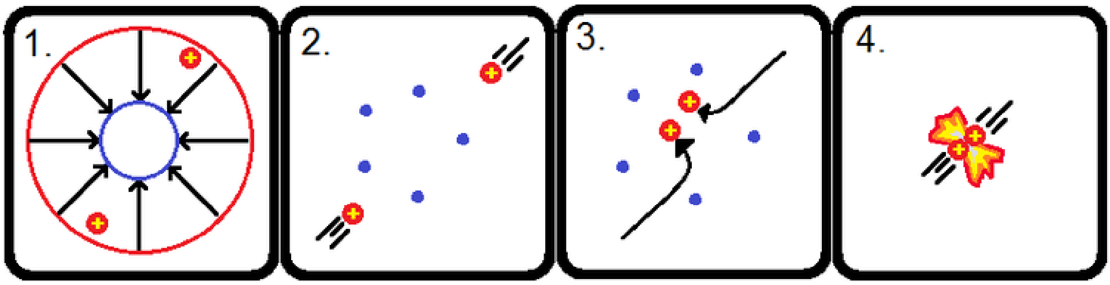

Figure 9

This is an illustration of the basic mechanism of fusion in fusors. (Figure 9) Firstly, the fusor contains two concentric wire cages. The cathode is inside the anode. Secondly, positive ions are attracted to the inner cathode. They fall down the voltage drop. The electric field does work on the ions heating them to fusion conditions. Then the ions miss the inner cage. Finally, the ions collide in the center and may fuse. [13]

4.2.2.3 The possible design of a fusion power plant

The various features such as steam generator, turbine and current generator will be the same as in conventional nuclear or fossil-fueled power plants. A flow chart of the energy and material flows in a fusion plant are depicted in figure III. The fuel - deuterium and tritium - is injected into the plasma in the form of a frozen pellet so that it will penetrate deeply into the center. The neutrons leave the plasma and are stopped in the so-called blankets which are modules surrounding the plasma. The neutrons deposit all their kinetic energy as heat in the blanket.

The blankets also contain lithium in order to breed fresh supplies of tritium via a nuclear reaction. The "ash" of the fusion reaction – helium – is removed via the diverter. This is the section of the containing vessel where the particles leaving the plasma hit the outer wall. The outer magnetic field lines of the tokamak are especially shaped so that they intersect the wall at special places, namely the diverter plates. Only a small fraction of the fuel is "burnt" so that deuterium and tritium are also found in the “exhaust” and can be re-cycled. The tritium produced in the blankets is extracted with a flushing gas - most likely helium - and delivered to the fuel cycle.

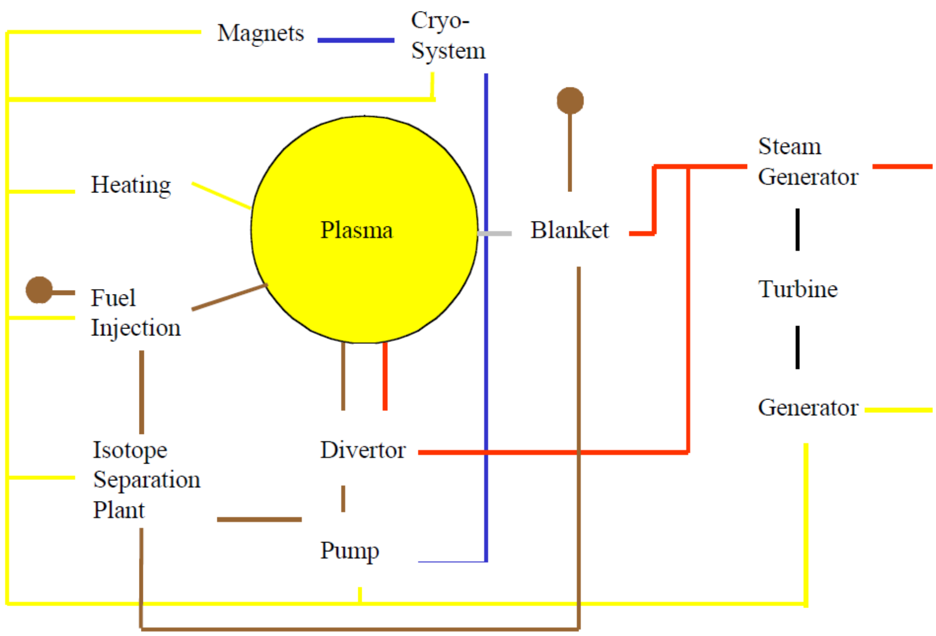

Figure 10: Flow chart for a future fusion reactor: fuel (brown), electrical power (yellow), heat (red), neutron (grey), mechanical power (black) and cooled helium (blue).

The heat produced in the blanket and the diverter is transported via water or helium to the steam generator and used to produce electricity to feed to the grid. A small fraction is used to supply electricity to the various components in the plant itself. Electrical power is required mainly for the cryo-system which produces low temperature helium for the super-conducting magnets, the current in the magnets, the current drive and the plasma heating systems.

The reactor core is arranged in different layers like an onion. The inner region is the plasma, surrounded by first wall and blanket. All this is contained in the vacuum vessel. Outside the vacuum vessel are the coils for the magnetic field. Since the magnets operate at very low temperatures (superconductors), the whole core is inside a cryostat. [14]

Conclusion

Nuclear fusion is now becoming a world-wide technical focus because of its productivity of energy. If the reaction of nuclear fusion can be controlled by we human beings, it is more than likely that humans don't have to worry about the energy shortage for a long time. I have basically introduced how fusion works in the paper, so I hope it will be feasible to bring controlled fusion back to reality and help us.

Bibliography

[1] [8] [9] [10] Nuclear fusion." Wikipedia. Wikimedia Foundation, 15 July 2017. Web. 16 July 2017

[2] [3] [6] [7] [14] Hamacher, T., and A. M. Bradshaw. "Fusion as a future power source: recent achievements and prospects." 18th world energy congress. 2001.

[4] [5] [11] "核聚变." Wikipedia. Wikimedia Foundation, n.d. Web. 16 July 2017

[12] "Controlled Thermonuclear Fusion." Control thermonuclear fusion. N.p., n.d. Web. 16 July 2017

[13] "Inertial electrostatic confinement." Wikipedia. Wikimedia Foundation, 16 June 2017. Web. 16 July 2017