DELHI PUBLIC SCHOOL BOPAL AHMEDABAD

KALOREX
Shaping Glocal Learners

सृJAN

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VIGYANAM

Awards This Certificate

To Sashwat Jain

School Udgam School for Children

Position Group - B (Runner Up)

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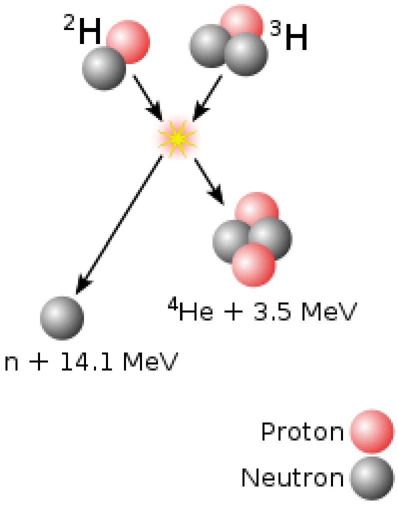
Principal

NUCLEAR FUSION

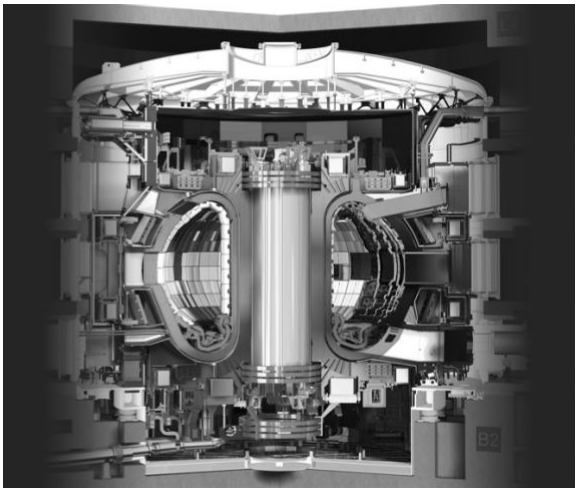
A limitless form of energy

- Sashwat Jain and Goral Mashru

Introduction



D+T Fusion



The tokamak at ITER

A nuclear fusion reaction is the process in which two lighter nuclei merge to form a single heavier nucleus

In most fusion reactions, the total mass of the reactants is more than the total mass of the products. This is because some of the reactants' mass is converted into energy. This process is explained by Einstein's equation: $E = mc^2$, which says in part that mass and energy can be converted into each other. Thus, nuclear fusion reactions are accompanied by the release of a substantial amount of energy. These are essentially the reactions that power the sun and other stars.

Historically, nuclear reactions were exploited to create thermonuclear weapons in the decade following World War II. However, the potential peaceful applications of the nuclear fusion reaction, like the huge amount of energy that it would produce, encouraged an immense effort to harness this process to produce power via fusion.

Development of Fusion Reactions

Fusion reactions in stars are initiated by the "burning" of Hydrogen, leading to the formation of Helium. However, generation of fusion energy for practical use involve reaction between the heavier isotopes of Hydrogen – Deuterium and Tritium. This is because they react more efficiently with each other and yield more energy per reaction than do two Hydrogen nuclei. The hydrogen nucleus consists of a single proton. The deuterium nucleus has one proton and one neutron, while tritium has one proton and two neutrons.

Requirements to Initiate a Fusion Reaction

1. Determination of Cross Section

When a particle passes through a collection of particles, they are likely to interact, by simple scattering or by undergoing a nuclear fusion reaction. The probability that the particles will interact is measured by a quantity called the ***nuclear cross section***. The magnitude of cross section depends on type of interaction and the state and energy of the particles. The product of the cross section and the atomic density of the target particle is called the macroscopic cross section. The inverse of the macroscopic cross section gives the mean free path, which is the mean distance an incident particle will travel before interacting with the target particle.

Nuclear cross section is measured by projecting a beam of particles at a given energy to interact with a thin target made of the same or different material. The deflections and reaction products are then measured to determine the cross product. This can be done for different reactions to determine the probability of occurrence of one type of fusion reaction versus another, as well as the optimal conditions for a particular reaction.
Cross sections of various types of reactions over a wide range of particle energies have been determined, by experimental measurement or theoretical calculation. They are well known for practical fusion energy applications and reasonably well known for stellar evolution.

Formula for measuring nuclear cross section:

$$r_x = \Phi\ \sigma_x\ \rho_A = \Phi \Sigma_x$$

2. Overcoming the Coulomb Barrier
For fusion reactions to take place, each of the two participating nuclei should have a positive charge of one or more. But we know that positively charged nuclei exert a repulsive force on each other which is inversely proportional to the square of the distance separating them. This repulsion is called Coulomb barrier. Thus, for two charged nuclei to come close enough to react, they should have enough energy to overcome the Coulomb barrier. The energy of the particles should be at least 104 election volts (1 eV ≅ 1.602 × 10^{-19} joule), often more than 105 or 106 eV. Therefore, the center of a star must be hot enough for the fuel to burn. Similarly, practical fusion energy systems must be heated to at least 50,000,000 K (90,000,000 °F) for reasonable rate of fusion and power output.

3. Achieving Plasma State

A plasma state is achieved when a gas' constituent atoms and molecules have been ionized by dissociation of one or more of their electrons. Due to the presence of free electrons, it can conduct electricity. Plasma state is attained at very high temperatures, implying that the ratio of neutral atoms to charged particles is very small. For example, the ionization energy of hydrogen is 13.6 eV, while the average energy of a hydrogen ion in plasma state at 50,000,000 K is 6,462 eV. Thus, essentially all the hydrogen in this plasma would be ionized. Since this has a high temperature, the nuclei have sufficient energy to overcome the coulomb barrier. Thermonuclear reactions can occur in a self-sustaining manner only if the fuel is in plasma state.

Rate and Yield of Fusion Reaction

Binding Energy

Binding energy of a nucleus is the measure of the efficiency with which its constituent nucleons are bound together. Say an element has Z protons and N neutrons is the nucleus. Then the binding energy B of the element will be stated as follows:

$B = (Z \cdot m_p + N \cdot m_n - M)\, c^2$

Z = number of protons, N = number of neutrons, m_p = mass of a proton, m_n = mass of a neutron, M = mass of the nucleus, c = speed of light (29,97,92,458 m/s)

Thus, the binding energy B is the energy associated with the mass difference between the Z protons and N neutrons considered separately and the nucleons bound together (Z + N) in a nucleus of mass M.

Experimental calculations have determined that the binding energy per nucleon is maximum of about 1.4×10^{-12} joule at an atomic mass number of 60 (iron). Accordingly, the fusion of elements lighter than iron or the splitting of heavier ones generally leads to a net release of energy.

Energy released in fusion reactions

Suppose two nuclei, X and a, react to form two other nuclei, Y and b. The reaction will be as follows:

$X + a \rightarrow Y + b$.

If the total mass of reactants is greater than the total mass of the products, which means that some mass was converted into energy, then the energy released from the reaction (Q) will be calculated by the following formula:

$$\mathbf{Q_{\text{energy released}} = (m_x + m_a - m_b - m_y)\, c^2}$$

Here the m-letters refer to masses of each of the particles respectively, and c is the speed of light.

When the value of Q is positive, the reaction is exoergic; when Q is negative, the reaction is endoergic.

When the total mass is conserved in the reactions, then the energy released (Q) can be expressed in terms of binding energy B of each particle as follows:

$$\mathbf{Q_{\text{energy released}} = B_y + B_b - B_x - B_a}$$

The energy released in D-T fusion reaction is 2.8×10^{-12} joule. If one ton (1000 kg) of deuterium were to be consumed through the fusion reaction with tritium, the energy released would be 8.4×10^{20} joules, equivalent to energy produced by approximately 29 billion tons of coal.

Rate of fusion reactions

In the plasma state, all particles do not have the same energy. In simple plasmas, the energy distribution is given by the Maxwell-Boltzmann distribution law. The relationship between temperature T and average particle energy E is given as follows:

$E = 3kT/2$

$k = 8.62 \times 10^{-5}$ eV / kelvin (Boltzmann constant).

The intensity of nuclear fusion reactions in a plasma is derived by averaging the product of the particles' speed and their cross sections over a distribution of speeds corresponding to a Maxwell-Boltzmann distribution. The cross section for the reaction depends on the energy or speed of the particles. The averaging process yields a function for a given reaction that depends only on the temperature and can be denoted f(T). The rate of energy released (i.e., the power released) in a reaction between two species, a and b, is

$P_{ab} = n_a \cdot n_b \cdot f_{ab}(T)\, U_{ab}$

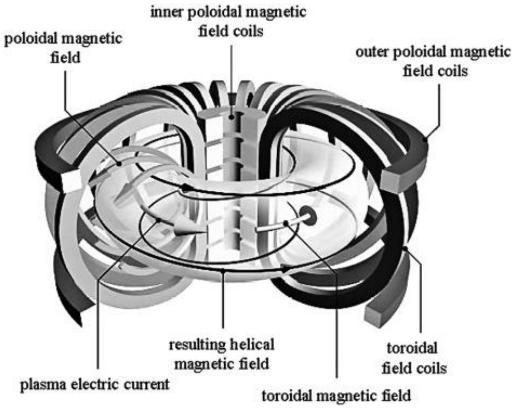
where n_a and n_b are the density of species a and b in the plasma, respectively, and U_{ab} is the energy released each time a and b undergo a fusion reaction. The parameter P_{ab} considers both – the rate of a given reaction and the energy yield per reaction.

Fusion reactions for controlled power generation

The most important fusion reactions for controlled power generation are those between deuterium and tritium. Their cross section for occurrence is high, practical plasma temperatures required for net energy release are moderate and energy yield of these reactions are quite high - 17.58 MeV for the basic D-T fusion reaction. In the deuterium plasma, two deuterium might react automatically to produce some tritium and helium-3. Other reactions involving elements with atomic number above 2 can be used, but the coulomb barrier increases with increase in charge of the nuclei, resulting in requirement of the plasma temperature to exceed 1,000,000,000 K if a significant rate is to be achieved.

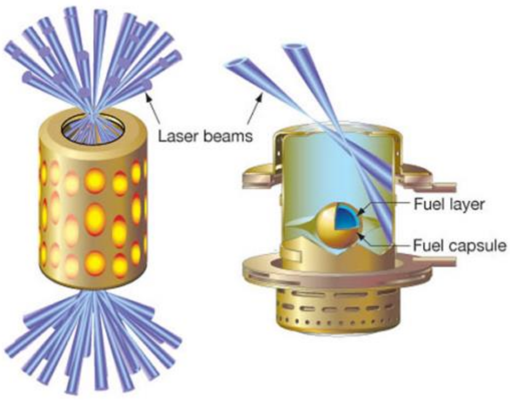
Methods of Achieving Fusion Energy

Magnetic Confinement



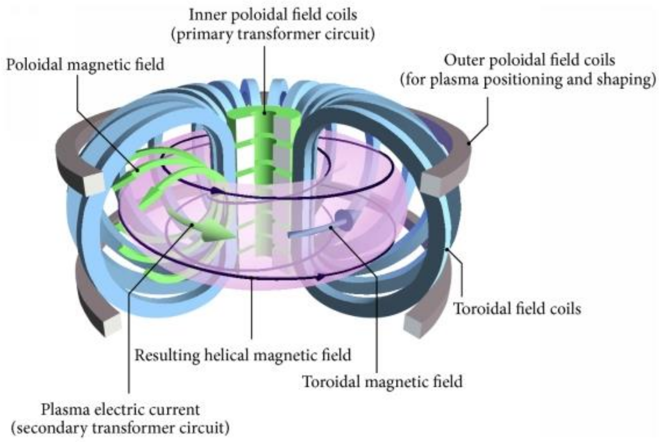
In magnetic confinement fusion, a large amount of Deuterium-Tritium plasma is confined by a magnetic field at a few atmospheres pressure and heated to a fusion temperature. The aim here is to prevent the particles from coming in contact with the reactor walls as this will slow them down and dissipate the heat. Magnetic field is effective in confining the plasma as the large number of charged particles will follow magnetic field lines. The most effective magnetic configuration is the doughnut shape or the toroidal, in which the magnetic field lines are curved to form a closed loop. A perpendicular field component called poloidal is superimposed upon the toroidal for proper confinement. This results in a magnetic field with force lines following a spiral (helical) path that confines and controls the plasma. The confined plasma is then heated to temperatures at which nuclear fusion is vigorous, typically greater than 75,000,000 K. Once the particles reach a high energy state, they start colliding and reacting.

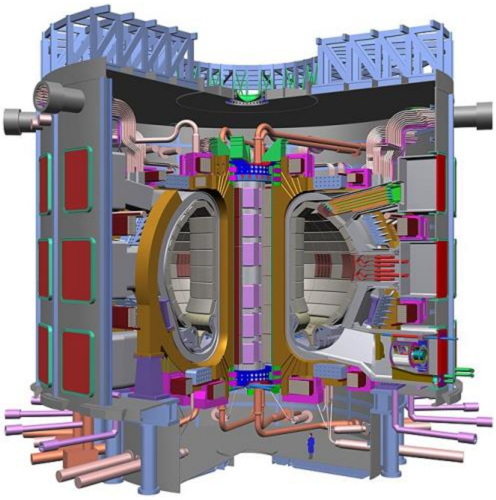
Inertial Confinement



In inertial confinement fusion, laser or ion beams are focused on the surface of small pellets of Deuterium-Tritium fuel, which are a few millimeters in diameter. This leads to heated of the outer layer, which explodes outward, generating an inward-moving compression. This leads to heating and compression of the inner layers. The core would be compressed to about 1000 times its liquid density, resulting in conditions for fusion reaction. The energy released form the reactions would heat the surrounding fuel, which may also undergo fusion leading to a chain reaction.

TOKAMAKS





TOKAMAK at ITER

A Tokamak is one out of 2 plasma confinement systems where a VERY strong magnetic field is induced into the plasma particles to keep it in one shape (in a torus shape).
Most scientists believe that tokamak is an ideal plasma confinement system for future fusion power plants although a company called Zap Energy Inc is against this point of view. They suggest that Electromagnetism is very power hungry and will increase the cost of achieving fusion

Need for fusion reactors

Although current methods of production of energy will be constantly upgraded and will be quite viable, nuclear fusion will be able to get us to a higher energy per unit area than any of its alternatives.

There are several reasons on why we should use nuclear fusion over other methods:

- The current methods of energy production are inefficient or have high carbon emissions. Nuclear fission is neither: It is supposed to have a high Q value which means that it is highly efficient, and it has no emissions.
- The fuel used for nuclear fusion is easily acquirable and the amount of fuel used is near nothing in comparison to nuclear fission
- No waste is produced in nuclear fission, no carbon emissions, and no risk of military use.
- No risk of a nuclear meltdown like Fukushima. If the worst-possible accident occurs i.e., leakage of fuel, the plasma will get decompressed and turn into its original state and have minimal damage.
- We will have abundant energy and have a very high energy density.

- Initially its cost will be higher that nuclear fission reactors but with time, its usage will become more ‘worth-the-money’.

Advancements in field of nuclear fusion:

1. The ITER tokamak

    The ITER (International Thermonuclear Experimental Reactor) is an international research and engineering project aiming to replicate the nuclear reactions of the Sun here on earth.
    Its main objective is to demonstrate the feasibility of fusion energy. The ITER tokamak will have a total capacity of 500 MW and a ‘Q’ value of ≥ 10. 300 MW of power will be used to infuse 50 MW into plasma and 500 MW of energy will be released.

2. Zap energy

    “Zap Energy’s technology stabilizes plasma using sheared flows rather than magnetic fields. Driving electric current through the flow creates the magnetic field, which confines and compresses the plasma. The higher the current, the greater the pressure and density in the plasma.” Zap energy’s view is that magnetic coils are too expensive and the method of storing plasma is too inefficient or unstable. Zap energy inc. is the only private (for profit) company in the nuclear fusion space and it might be the best organization in terms of understanding nuclear fusion and making it viable

3. Commonwealth Fusion systems:

    They don’t have a different approach, but they are doing everything systematically and they plan on commercializing fusion energy in 2025 and attain fusion in 2021.
4. Another point of view:

    The larger the volume of the tokamak, higher the initiation energy and lower the ‘q’ value.

    So, it can be hypothesized that exceeding the size of tokamaks over a certain amount will lead to lower efficiency and higher cost of generation/production of energy.

Resources

- https://www.energy.gov/science/doe-explainsnuclear-fusion-reactions
- https://www.britannica.com/science/nuclear-fusion/Energy-released-in-fusion-reactions
- https://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx
- https://en.wikipedia.org/wiki/Tokamak
- https://en.wikipedia.org/wiki/ITER
- https://en.wikipedia.org/wiki/Magnetic_confinement_fusion
- https://en.wikipedia.org/wiki/Inertial_confinement_fusion
- https://www.youtube.com/watch?v=mZsaaturR6E
- https://www.youtube.com/watch?v=mZsaaturR6E
- https://www.iter.org/
- https://www.zapenergyinc.com/
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