Production of energy in sun and stars

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Abstracts:

Fusion is the energy source of the sun and stars. In fusion, two light nuclei, such as hydrogen combine into one new nucleus such as helium and release enormous energy in the process. On earth, fusion has the potential to be an abundant and attractive source of energy for the future. The Sun has been radiating an enormous amount of energy at the present rate for nearly 5 billion years and will continue radiating at that rate for about 5 billion years more. Only a small part of solar energy reaches the outer layer of the earth's atmosphere. Nearly half of it is absorbed while passing through the atmosphere and the rest reaches the earth's surface.

Keywords: Fusion, Fission, Corona, Solar wind, Stellar Energy, Binding energy

1.1 Introduction:

Nuclear fusion is the process in which the two light nuclei combine to form a heavy nucleus. In this process also huge amount of energy is released. The cause of energy release is that the binding energy increases due to fusion. From the binding energy curve, we find that for the nuclei of mass number A<12, the binding energy per nucleon is low and when two light nuclei combine to form a nucleus, the binding energy per nucleon of the product nucleus is more as compared to the binding energy per nucleon of the combining nuclei. In other words, the mass of the product nucleus is less than the sum of masses of the two combining nuclei. This loss in mass is released in form of energy according to the mass-energy equivalence relation $\Delta E = (\Delta m)\, c^2$. For example, when two deuterium nuclei fuse together, 3.3 MeV energy is released and the nucleus of helium isotope is formed. This helium isotope again gets fused with one deuterium nucleus to form a helium nucleus and 18.3 MeV energy is released in this process. The nuclear reactions are:

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.3\ \text{MeV} $$

(Deuterium) (Deuterium) (Helium isotope) (Neutron)

$$^{3}_{2}He + ^{2}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{1}H + 18.3\ MeV$$

(Helium isotope) (Deuterium) (Helium) (Proton)

Thus, in all, three deuterium nuclei fuse to form a helium nucleus with a release of 21.6 MeV energy. A part of this energy is obtained in form of kinetic energies of neutron ($^{1}_{0}n$) and proton ($^{1}_{1}H$). The process of nuclear fusion is not possible at ordinary temperature and pressure. But it can occur only at a very high temperature ($\approx 10^7$ K) and high pressure. The reason is that as the combining nuclei approach each other. They experience a strong electrostatic repulsive force due to their positive charges; as a result they get far separated. But if these nuclei are imparted energy nearly 0.1 MeV or more than it, they overcome the electrostatic repulsive force acting between them and then if they are brought too closer that the short range nuclear attractive forces begin to act between them, the two nuclei can fuse together. Moreover, for the fusion reaction to take place, the nuclei must be placed in a region where they can collide each other without any absorption or attenuation of energy.

For example if we take the mass of proton = 1.00728 a.m.u., mass of neutron = 1.00898 a.m.u., mass of deuteron nucleus = 2.01444 a.m.u., and mass of helium nucleus = 4.00387 a.m.u., then the mass defect in the above fusion reaction is

$$\Delta m = [3 \times m\left(^{2}_{1}H\right) - m\left(^{4}_{2}He\right) - m\left(^{1}_{0}n\right) - m\left(^{1}_{1}H\right)]$$

[3x2.01444 – 4.00387 – 1.00898 -1.00728] a.m.u.
= 0.02320 a.m.u.

Hence the energy released $E = \Delta mc^2$ = 0.02320 x 931 MeV (Since 1 a.m.u. = 931 MeV)
= 21.6 MeV

1.2 Structure of the Sun

The core of the Sun extends from the center to about 20–25% of the solar radius. It has a density of up to150 g/cm (about 150 times the density of water) and a temperature of close to 15.7 million kelvins (K). By contrast, the Sun's surface temperature is approximately 5,800 K. Recent analysis of SOHO mission data favors a faster rotation rate in the core than in the radiative zone above. Through most of the Sun's life, energy is produced by nuclear fusion in the core region through a series of steps called the p–p(proton–proton) chain, this process converts hydrogen into helium. Only 0.8% of the energy generated in the Sun comes from the CNO cycle, though this proportion is expected to increase as the Sun becomes older.

The core is the only region in the Sun that produces an appreciable amount of thermal energy through fusion, 99% of the power is generated within 24% of the Sun's radius and by 30% of the radius, fusion has stopped nearly entirely. The remainder of the Sun is heated by this energy as it is transferred outwards through many successive layers, finally to the solar photosphere where it escapes into space as sunlight or the kinetic energy of particles.

The proton–proton chain occurs around 9.2×10^{37} times each second in the core, converting about 3.7×10^{38} protons into alpha particles (helium nuclei) every second (out of a total of ~8.9×10^{56} free protons in the Sun) or about 6.2×10 kg/s. Fusing four free protons (Hydrogen nuclei) into a single alpha particle (Helium nuclei) releases around 0.7% of the fused mass as energy, so the Sun releases energy at the mass energy conversion rate of 4.26 million metric tons per second, for 384.6 yottawatts (3.846×10^{26} W) or 9.192×10^{10} megatons of TNT per second. Theoretical models of the Sun's interior indicate a power density of approximately 276.5 W/m^3, a value that more nearly approximates reptile metabolism than a thermonuclear bomb.

The fusion rate in the core is in a self-correcting equilibrium: a slightly higher rate of fusion would cause the core to heat up more and expand slightly against the weight of the outer layers, reducing the density and hence the fusion rate and correcting the perturbation and a slightly lower rate would cause the core to cool and shrink slightly, increasing the density and increasing the fusion rate and again reverting it to its present rate. Following figure shows the structure of sun.

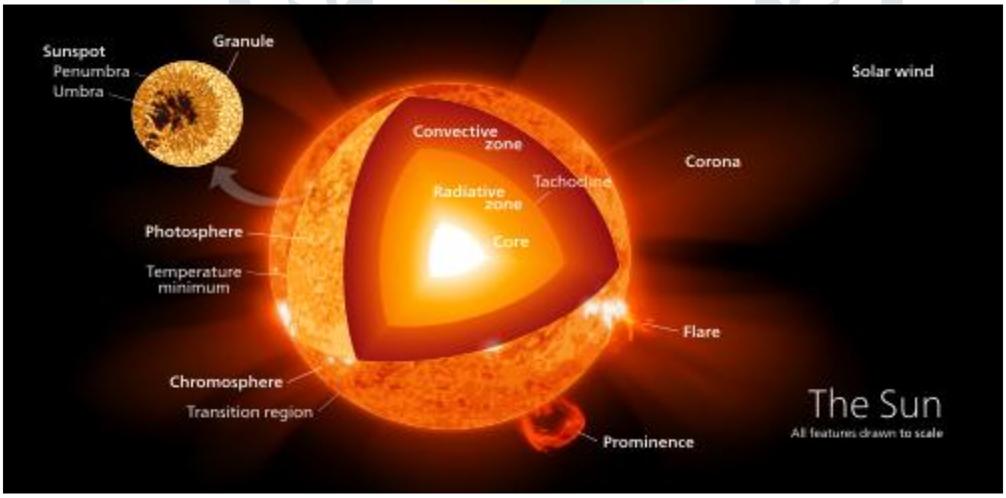


Figure-1: Structure of the Sun

1.3 Comparison between nuclear fusion and nuclear fission:

Although it appears that the energy obtained from nuclear fusion is very small as compared to the energy obtained from nuclear fission, but actually it is not so. For a given mass, the energy obtained from the fusion of light nuclei is very large as compared to the energy obtained from the fission of a heavy nucleus for the same mass. The reason for it is that the number of light nuclei in a given mass is very large as compared to the number of heavy nuclei, for the same mass.

For example, Number of deuteron nuclei $\left({}_1^2H\right)$ in 1 g $= \frac{6.02 \times 10^{23}}{2} = 3.01 \times 10^{23}$

Since 21.6 MeV energy is released due to fusion of three deuteron nuclei, therefore energy, obtained from

1 g deuteron $= \frac{21.6 \times (3.01 \times 10^{23})}{3} = 2.17 \times 10^{24}$ MeV

Now number of uranium nuclei $({}_{92}^{235}U)$ in 1 g $= \frac{6.02 \times 10^{23})}{235} = 2.56 \times 10^{21}$

Since 190 MeV energy is released due to fission of 1 uranium nucleus, therefore energy obtained from 1 g uranium

$= 190 \times (2.56 \times 10^{21})$

$= 4.86 \times 10^{23}$ MeV or 0.486×10^{24} MeV

Obviously the energy obtained due to fusion of 1 g deuterium is nearly 4.5 times the energy obtained due to fission of 1 g uranium. This is the reason that these days scientists are engaged in getting energy by the process of fusion, because deuterium can be obtained in abundance at a very low cost from the sea water. But it is very difficult to fuse the two light nuclei as compared to fission of a heavy nucleus.

1.4 Condition for Fusion Reaction:

We have read that the fusion reaction is more useful than the fission reaction. But the fusion reaction will be fruitful only if the reaction once started, continues and we continuously get the energy i.e., the reaction is self sustaining, For the sustained fusion reaction, following three conditions are required:

(i) The energy of nuclei fusing together must be nearly 0.1 MeV or more than it so that they can overcome the electrostatic repulsive force acting between them due to their positive charges and they can approach each other such that the short range nuclear attractive forces may act between them. For this, a very high temperature (nearly 10^7 k) and a high pressure is required. At such a high temperature the nuclei, due to their thermal motion, acquire sufficient kinetic energy to overcome the electrostatic repulsive force acting between them when they are brought closer and they get fused.

(ii)The fusing nuclei should be placed in a region where they can collide with each other without any attenuation or absorption of energy.

(iii)At a high temperature ($\approx 10^7$K), the substance gets ionized (i.e, from the atoms of the substance, electrons and positive ions of nuclei get separated). This is called the plasma state of the substance. Thus, there should be a proper arrangement for the confinement of plasma, which is a very difficult task.

1.5 Energy Production in Stars:

We know that the sun and the stars are continuously emitting energy for the last several years. The sun emits nearly $4x10^{26}$ joule energy per second. We get evidences from the astronomical and geo-scientific observations that the sun is emitting energy at this rate from billions of years. According to the Einstein's mass-energy equivalence, the mass of sun should decrease at a rate of nearly 4.4×10^9 kg per second to impart this much amount of energy. If the source of this energy in sun and stars, is the nuclear reaction, then it is essential that

(i)The reaction is exoergic i.e, the sum of masses of products of nuclear reaction should be less than the sum of masses of the reactants.

(ii)The reaction should be such that it is possible at the high temperature available inside the sun or stars.

(ii)The reactants of nuclear reaction must be available in abundance in the sun and the stars.

One this basis, there are different views of scientists regarding the source of unlimited energy of sun and stars. Some of the views are given below:

(1)According to Helmholtz, the sun and the stars are continuously contracting due to which their gravitational potential energy is continuously decreasing and this energy is changing into the heat energy. But this cannot be the source of sun's and stellar energy because on calculations we find that the energy produced due to contraction of sun and stars is only 1% of the actual energy emitted from them.

(2)The source of sun's and stellar energy is the natural radioactive decay or nuclear fission of heavy nuclei. But this cannot be the source because the presence of heavy elements in sun and stars is so low that there cannot be the emission of energy at such a higher rate.

(3) According to the modern views, the source of sun's and stellar energy is the fusion of light nuclei present in them.

1.6 Fusion reaction in Sun and Stars:

The temperature of the sun's surface is nearly 6000 K and the temperature at its centre (nucleus) is nearly 2×10^7 K. It is also definite that inside the nucleus of sun, heavy elements are not in abundance. Nearly 90% part of sun is made up of light elements such as hydrogen and helium. At such a high temperature ($\approx 10^7$ K), these light elements inside the sun are in the plasma state. Hence, the main source of this energy is the conversion of hydrogen nuclei by the process of fusion into the helium nucleus at such a high temperature inside the nucleus of sun. Similarly, the temperature of nucleus of other stars is also so high that the substance present inside the nucleus is in ionized state (or plasma state). Hence the source of stellar energy is also the fusion of hydrogen nuclei at a high temperature to form the helium nucleus. In this process, a tremendous amount of energy is released. The reaction is

$$ {}_{1}^{1}\mathrm{H} + {}_{1}^{1}\mathrm{H} + {}_{1}^{1}\mathrm{H} + {}_{1}^{1}\mathrm{H} \longrightarrow {}_{2}^{4}\mathrm{He} + 2\,{}_{+1}^{0}\beta + 2\upsilon + energy\ (26.7\ MeV) $$

(Four hydrogen) (Helium) (Positron) (Neutrino)

Thus in this process, four hydrogen nuclei fuse to form a helium nucleus with a release of 26.7 MeV energy.

For the above fusion process, there are the following two theories:

(1) Proton-Proton (P-P) Cycle and (2) Carbon-Nitrogen (C-N) Cycle.

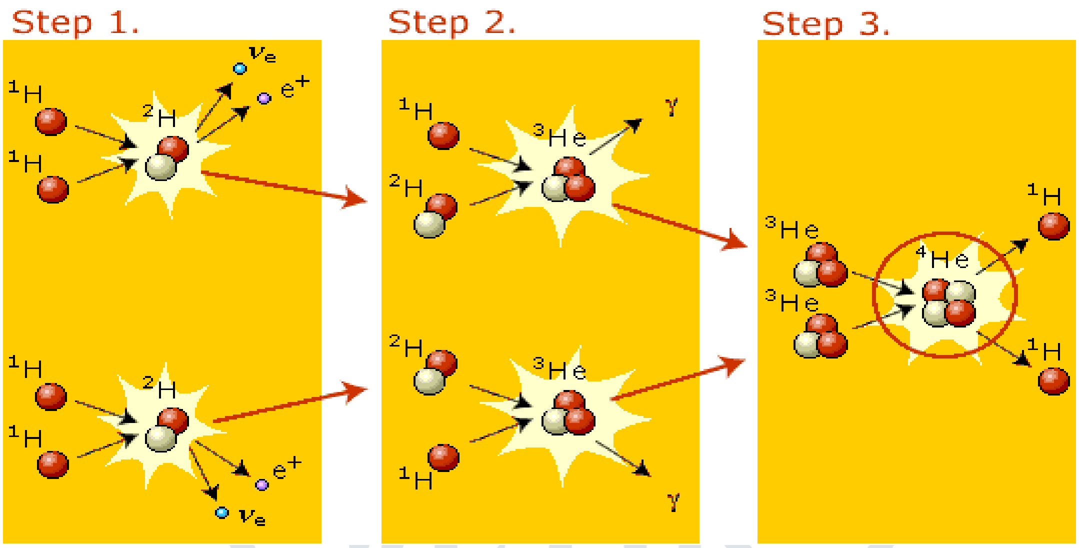
1.6.1 Proton- Proton Cycle (P-P Cycle)

According to this theory, the fusion reactions of hydrogen nuclei inside the sun and stars are as

$$ {}_{1}^{1}\mathrm{H} + {}_{1}^{1}\mathrm{H} \rightarrow {}_{1}^{2}\mathrm{H} + {}_{+1}^{0}\beta + \upsilon $$

$$ {}_{1}^{2}\mathrm{H} + {}_{1}^{1}\mathrm{H} \rightarrow {}_{2}^{3}\mathrm{He} + \gamma $$

And $$_{2}^{3}He + _{2}^{3}He \rightarrow _{2}^{4}He + _{1}^{1}H + _{1}^{1}H$$



Multiplying the first two equations by 2 and then adding in the third equation, we get

$$_{1}^{1}H + _{1}^{1}H + _{1}^{1}H + _{1}^{1}H \longrightarrow _{2}^{4}He + 2\, _{+1}^{0}\beta + 2v + \gamma - rays$$

In this cycle, 4 hydrogen nuclei fuse to form one helium nucleus ($_{2}^{4}He$) with a release of 2 positrons and 24.7 MeV energy. These positrons annihilate with two electrons with a release of 2 MeV energy. Thus total energy released in this reaction is 26.7 MeV. Figure-2 shows this cycle.

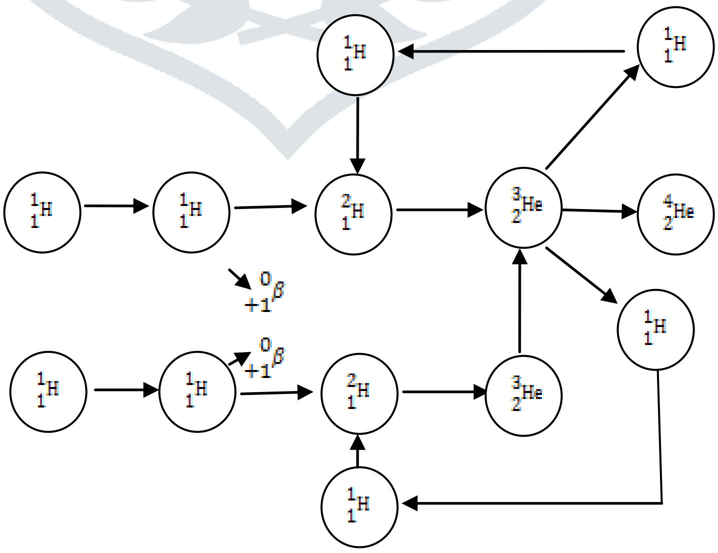
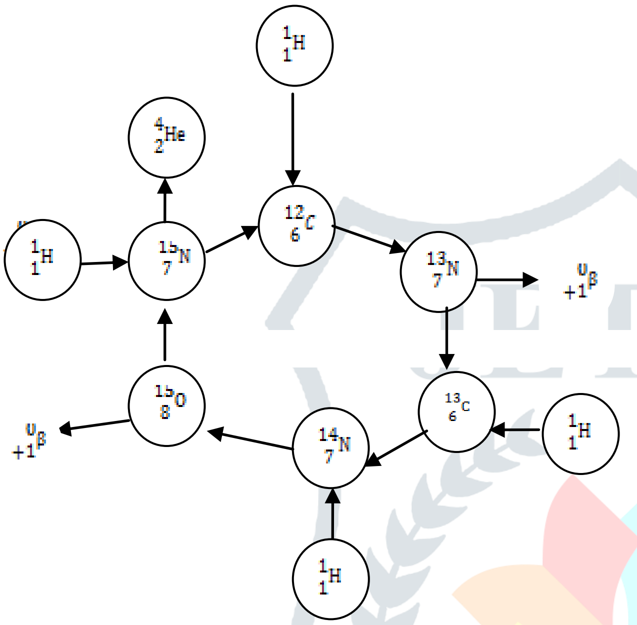


Figure-2: P-P Cycle

1.6.2 Carbon-Nitrogen Cycle (C-N Cycle)

According to the theory propounded by Bethe in 1939, the Carbon nucleus acts like a catalyst in the fusion reaction and it is not lost. It only takes part in the reaction and then at the end of reaction, it is re-obtained. Actually the four hydrogen nuclei fuse to form a helium nucleus. There are the following six reactions in this cycle:



(i) $^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}H + \gamma$

(ii) $^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{+1}\beta + \upsilon$

(iii) $^{13}_{6}C + ^{1}_{1}H \longrightarrow ^{14}_{7}N + \gamma$

(iv) $^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{15}_{8}O + \gamma$

(v) $^{15}_{8}O \longrightarrow ^{15}_{7}N + ^{0}_{+1}\beta + \upsilon$

(vi) $^{15}_{7}N + ^{1}_{1}H \longrightarrow ^{12}_{6}C + ^{4}_{2}He$

Figure-3 C-N Cycle

Adding all these reaction we, get

$$^{1}_{1}H + ^{1}_{1}H + ^{1}_{1}H + ^{1}_{1}H \longrightarrow ^{4}_{2}He + 2\,^{0}_{+1}\beta + 2\upsilon + \gamma - rays\ (energy)$$

Thus, 4 hydrogen nuclei fuse to form a helium nucleus with a release of 2 positrons and 24.7 MeV energy. These positrons annihilate with two electrons and thus 2 MeV energy is emitted. Thus in this reaction, total 26.7 MeV energy is released. Since there are nearly 2 x 10^{23} protons (or hydrogen nuclei) in 1 g of the matter of sun or stars, hence a tremendous energy (=2 x 10^{23} x 26.7 =5.34 x 10^{24} MeV) is released from 1 g matter.

1.6.3 Calculation of Energy:

Mass of 1 hydrogen nucleus = 1.00728 a.m.u., mass of one helum nucleus = 4.00150 a.m.u., mass of positron = 0.00055 a.m.u.

Mass of 4 hydrogen nuclei = 4x1.00728 a.m.u. = 4.02912 a.m.u.

Mass of 1 helium nucleus = 4.00150 a.m.u.

Mass of 2 positrons = 2 x 0.00055 a.m.u. = 0.00110 a.m.u.

Hence, mass defect in one fusion reaction

Δm = Mass of 4 hydrogen nuclei – (Mass of helium nucleus + mass of 2 positrons)

= 4.02912-(4.00150+0.00110) = 0.02652 a.m.u.

Since 1 a.m.u. = 931 MeV

.:. Energy Released in one fusion reaction

$$\Delta E = (\Delta m)\ c2 = 0.02652 \times 931\ \text{MeV} = 24.7\ \text{MeV}$$

Two positron released in the fusion reaction annihilate with two electrons due to which nearly 2MeV energy is released. Thus, total energy released in the process of fusion = 24.7+2=26.7 MeV.

1.7 Conclusion:

India is lucky to receive solar energy for greater part of the year. It is estimated that during a year India receives the energy equivalent to more than 5,000 trillion Kwh. Under clear or cloudless sky conditions, the daily average varies from 4 to 7 Kwh/m2. The solar energy reaching unit area at outer edge of the earth's atmosphere exposed perpendicularly to the rays of the Sun at the average distance between the Sun and earth is known as the solar constant. It is estimated to be approximately 1.4 kJ per second per square meter or 1.4 kW/m2. The fusion of light nuclei can give more energy per kg material than fission. The energy produced by fusion of one litre of deuterium corresponds to the energy produced by combustion of 600 litres of gasoline. A particularly attractive possibility is to use heavy hydrogen, deuterium, which is available in sea water. In the world's oceans there is 10^{15} kg of deuterium available. Much research today is devoted to make temperatures sufficiently high for a fusion reactor to work. From the above study, it is found that the main source of solar and stellar energy is the fusion of hydrogen nuclei.

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