Thermonuclear Fusion

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Definition:

Nuclear fusion is a nuclear reaction in which two light nuclei (such as hydrogen) combine to form heavier nuclei (such as helium). The process releases excess binding energy from the reaction, based upon the binding energies of the atoms involved in the process.

Thermonuclear fusion in stars

Here we consider in more detail the thermonuclear fusion processes that take place in our sun and in other star. In the sun's deep interior, where the mass is concentrated and where most of the energy production takes place, the (central) temperature 1.5 × 107 k and the central density is on the order of 105 kg / m3, about 13 times the density of lead. The central temperature is so high that in spite of the high central pressure (2 × 1011 atm), the sun remains gaseous throughout.

The present composition of the sun's core is about 35% hydrogen by mass, about 65% helium, and about 1% other elements. At this temperature the light elements are essentially totally ionized, so that our picture is one of an assembly of proton, electrons, and α particle in random motion.

The sun radiates at the rate of 3.9 × 1026 w and has been doing so for as long as the solar system has existed , which is about 4.5 × 109 y. It has been known since the 1930s that thermonuclear fusion processes in the sun's interior account for its prodigious energy output. Before analyzing this further, however, let us dispose of two other possibilities that had been put forward earlier. Consider first chemical reaction such as simple burning. If the Sun, whose mass is 2 × 1039 kg, is made of coal and oxygen in just the right proportions for burning, it would last only about 103 y, which of course is far too short. The sun, as we shall see, does not burn coal but hydrogen, and in a nuclear furnace, not an atomic or chemical one.

Another possibility is that, as the core of the sun cools and the pressure there drops, the sun will shrink under the action of its own strong gravitational forces. By transferring gravitational potential energy to internal energy (just as we do when we drop a stone onto the Earth's surface), the temperature of the sun's core will rise so that radiation may continue. Calculation shows, however, that the sun could radiate from this cause for only about 108 y, too short by a factor of 25.

The sun's energy is generated by the thermonuclear "burning" (That is, “fusing ”) of hydrogen to form helium. Figure (1) shows the proton – proton cycle by which this is accomplished. Note that each reaction shown is a fusion reaction, in that one of the products (2H, 3He or 4He) has a higher mass number than any of reacting particles that form it. The reaction energy Q for each reaction shown in figure (1) is positive. This characterizes an exothermic reaction, with the net release of energy. The cycle is initiated by the collision of two protons (1H + 1H) to form a deuteron (2H), with the simultaneous creation of a positron (e +) and a neutrino (v). The positron very quickly encounters a free electron (e-) in the sun and both particles annihilate, their rest energies appearing as two gammas – ray photons (γ). In figure (1) we follow the consequences of two such events, as indicated in the top row of the figure. Such events are extremely rare. In fact, only once in about 1026 proton – proton collisions is a deuteron formed; in the vast majority of cases the colliding protons simply scatter from each other. It is the slowness of this process that regulates the rate of energy production and keeps the sun from exploding. In spite of this slowness, there are so very many protons in the huge volume of sun’s core that deuterium is produced there in this way at the rate of about 1012 kg / s!

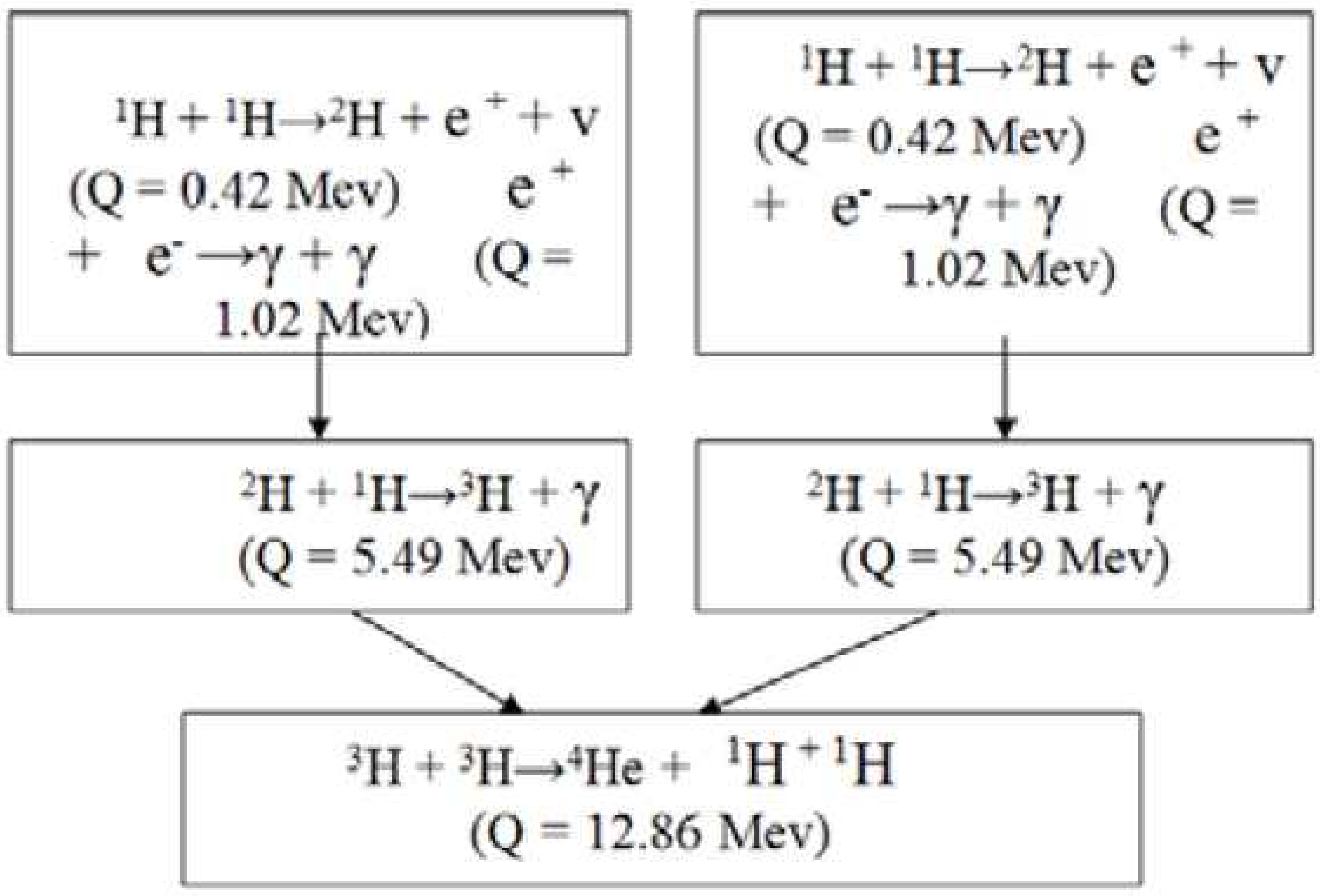

Figure (1) The proton – proton cycle that primary accounts for energy production in the sun

Once a deuteron has been product, it quickly (within a few second) collides with another proton and forms a (3He) nucleus, as the second row of fig (1) shows. Two such (3He) nuclei may then eventually (within about 105 y) collide forming a particle (4He) and two protons, as the third row of the figure shows. There are other variations of the proton – proton cycle, involving other light elements, but we concentrate on the principal sequence as represented in fig (1).

Taking an overall view of the proton – proton cycle, we see that it amounts to the combination of four proton and two electrons to form an α particle, two neutrinos, and six gamma rays:

$$41H + 2e- \longrightarrow 4He + 2v + 6\gamma. \qquad (1)$$

Now, in a formal way, let us add two electrons to each side of equation (1) yielding

$$4(1H + e-) \rightarrow (4He + 2\ e-) + 2v + 6\gamma. \qquad (2)$$

The quantities in parentheses then represent atoms (not bare nuclei) of hydrogen and of helium. The energy release in the reaction of equation (2) is using the atomic masses of hydrogen and helium,

$Q = (mi - mf)\ c2$

$c2\ [\ 4m\ (1H) - m\ (4He)\ ]\ Q = [4(1.007825\ u\ ) - 4.002603\ u\ ](\ 931.5$
$Me\ \ =26.7MeV =$

(Gamma – ray photons are massles, and neutrino have either zero or negligibly small mass; thus neither particle enters into the calculation of the Q value for the fusion reaction.) This same value of Q follows (as it must) by adding up the Q values for the separate steps of the proton – proton cycle in figure (1).

Not quite all this energy is available as internal energy inside the sun. About 0.5 MeV is associated with the two neutrinos that are produced in each cycle. Neutrinos are so penetrating that in essentially all cases they escape from the sun, carrying this energy with them. Some are intercepted by the Earth, bringing us our only direct information about the sun›s interior.

Subtracting the neutrino energy leaves 26.2 MeV per cycle available within the sun .this corresponds to a “heat of combustion « for the nuclear burning of hydrogen into helium of 6.3 × 1014 J/kg of hydrogen consumed . By comparison, the heat of combustion of coal is about 3.3 × 107 J/kg, some 20 million times lower, reflecting roughly the general ratio of energies in nuclear and chemical processes.

We may ask how long the sun can continue to shine at its present rate before all the hydrogen in its core has been converted into helium. Hydrogen burning has been going on for about 4.5 × 109 y, and calculations show that there is enough hydrogen left for about 5 × 109 y more.

At that major changes will begin to happen. The sun’s core, which by then will be largely helium, will begin to collapse and to heat up while the outer envelope will expand greatly, perhaps so far as to encompass the Earth's orbit. The sun will become what astronomers call a red giant.

If the core temperature heats up to about 108 K, energy can be produced by burning helium to make carbon. Helium does not burn readily, the only possible reaction being

4He +   4He + 4He → 12C + γ.

Such a three – body collision of three α particles must occur within 10-16 s if the reaction is to go. Nevertheless, if the density and temperature of the helium core are high enough, carbon will be manufactured by the burning of helium in this way. As a star evolves and becomes still hotter, other element can be formed by other fusion reaction, however, elements beyond A= 56 cannot be manufactured by further fusion processes but is fission processes. The elements with A = 56 (56Fe, 56Co, 56Ni) lie near the peak of the binding energy curve of figure (2), and fusion between nuclides beyond this point involves the consumption, and not the production, of energy.

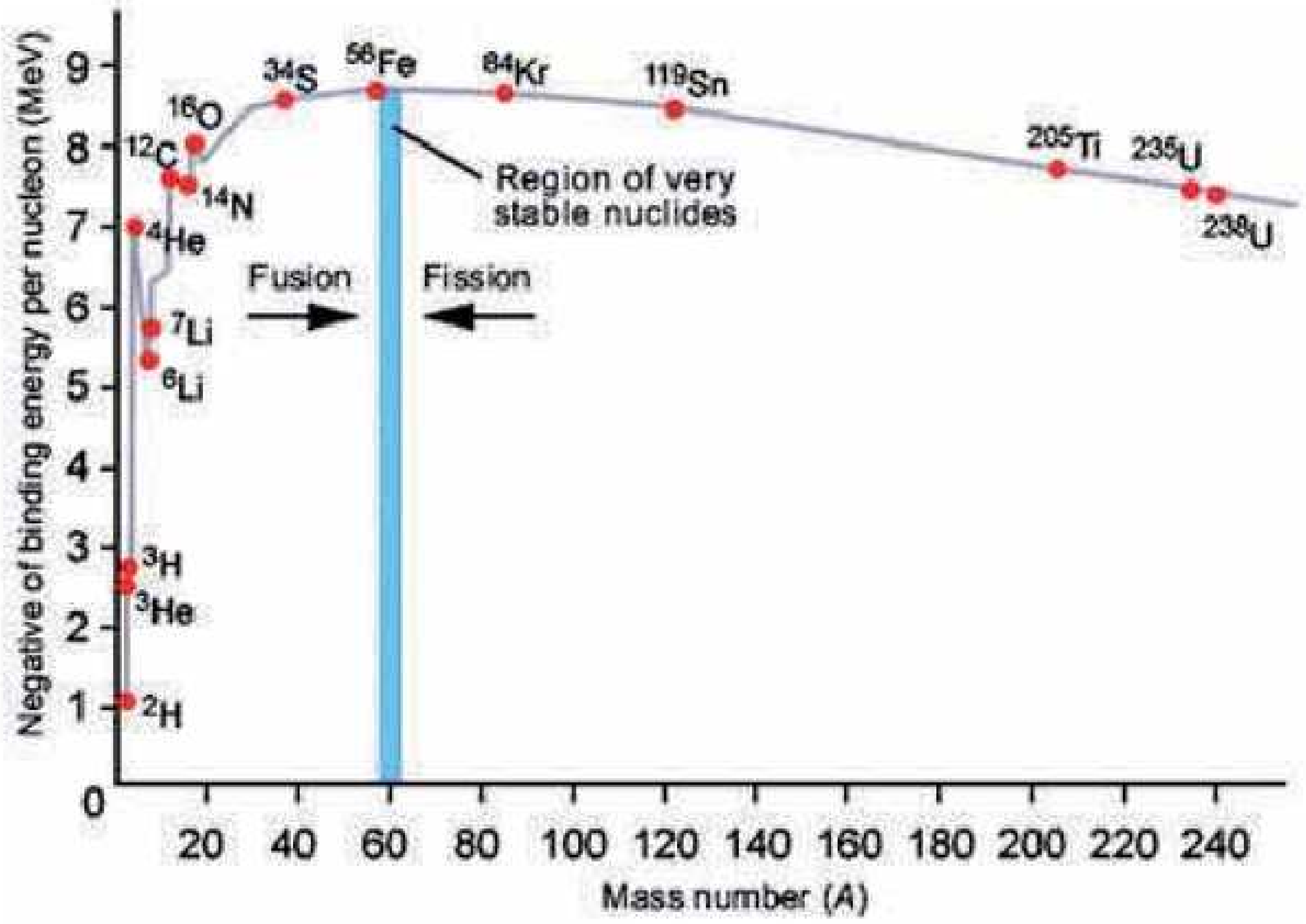

Figure (2) The binding energy per nucleon over the range of mass numbers.

Later in a star's lifetime it may yield other nuclear reaction, producing elements heavier than helium. In all these reaction a small amount of mass is converted into energy, as given by Einstein equation. (E = mc2) This means that stars are continuously reducing their mass, but because of the size of the c2 term the reduction is insignificant.

For many star the process ends with iron nuclei these nuclei are the most stable, and further fusion does not emit energy but rather requires it. Elements heavier than iron are made not in ordinary stars but mostly in a still poorly understood event called supernova, in which a massive star explodes in a flurry of nuclear activity. There is enough energy in these explosions to produce nuclei of all the heavy elements.

Applications:

One of the applications is Fusion weapons is called (hydrogen bomb) The process of combining nuclei (the protons and neutrons inside an atomic nucleus) together with a release of kinetic energy is called fusion. This process powers the Sun, it contributes to the world stockpile of weapons of mass destruction and may one day generate safe, clean electrical power.

This powerful but complex weapon uses the fusion of heavy isotopes of hydrogen, deuterium, and tritium to release large numbers of neutrons when the fusile (sometimes termed “fusionable”) material is compressed by the energy released by a fission device called a primary as shown in figure(3). Fusion (or ‘‘thermonuclear’ weapons derive a significant amount of their total energy from fusion reactions. The intense temperatures and pressures generated by a fission explosion overcome the strong electrical repulsion that would otherwise keep the positively charged nuclei of the fusion fuel from reacting.

The first thermonuclear devices used liquid fuel, such as deuterium, which required significant developments in cryogenics to keep the fuel below its boiling point of -250 C. Later devices used lithium deuteride fuel, in solid form, which breeds tritium when exposed to neutrons.

It is inconvenient to carry deuterium and tritium as gases in a thermonuclear weapon, and certainly impractical to carry them as liquefied gases, which requires high pressures and cryogenic temperatures. Instead, one can make a “dry” device in which 6Li is combined with deuterium to form the compound 6Li D (lithium-6 deuteride). Neutrons from a fission “primary” device bombard the 6 Li in the compound, liberating tritium, which quickly fuses with the nearby deuterium.

The a particles, being electrically charged and at high temperatures, contribute directly to forming the nuclear fireball. The neutrons can bombard additional 6Li nuclei or cause the remaining uranium and plutonium in the weapon to undergo fission. This two-stage thermonuclear weapon has explosive yields far greater than can be achieved with one point safe designs of pure fission weapons, and thermonuclear fusion stages can be ignited in sequence to deliver any desired yield. Such bombs, in theory, can be designed with arbitrarily large yields: the Soviet Union once tested a device with a yield of about 59 megatons.

In a relatively crude sense, 6 Li can be thought of as consisting of an alpha particle (4He) and a deuteron (2H) bound together. When bombarded by neutrons, 6 Li disintegrates into a triton (3 H) and an alpha:

6 Li + Neutron = 3 H + 3 He + Energy.

This is the key to its importance in nuclear weapons physics. The nuclear fusion reaction which ignites most readily is

2 H + 3 H = 4 He + n + 17.6 MeV,

or, phrased in other terms, deuterium plus tritium produces 4He plus a neutron plus 17.6 MeV of free energy:

2H + 3 H = 4 He + n + 17.6 MeV.

Lithium-7 also contributes to the production of tritium in a thermonuclear secondary, albeit at a lower rate than 6Li. The fusion reactions derived from tritium produced from 7 Li contributed many unexpected neutrons (and hence far more energy release than planned) to the final stage of the infamous 1953 Castle/BRAVO atmospheric test, nearly doubling its expected yield.

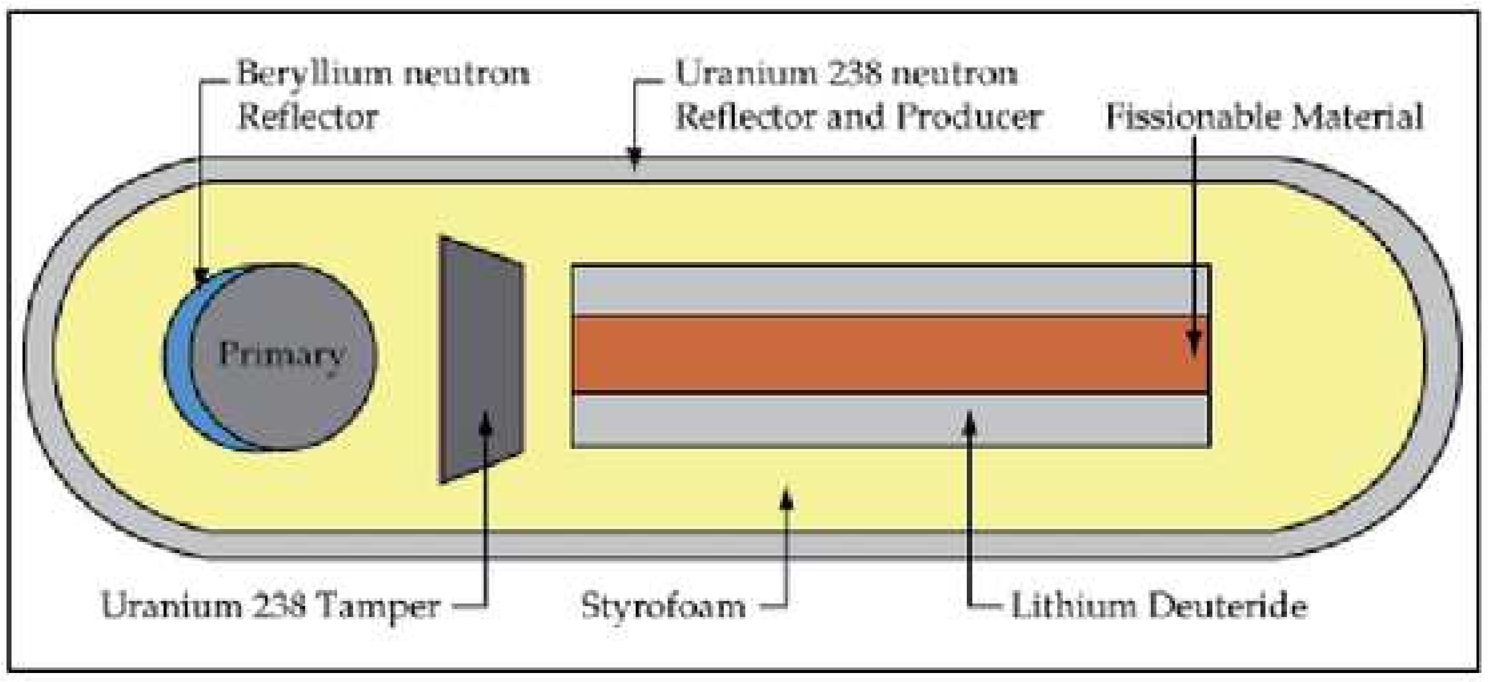

Figure (3) A hydrogen bomb: a fission bomb uses radiation to compress and heat a separate section of fusion fuel.

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