**Nuclear fusion**

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The Sun is a main-sequence star, and thus generates its energy by nuclear fusion of hydrogen nuclei into helium. In its core, the Sun fuses 620 million metric tons of hydrogen each second.

Nuclear Physics



In nuclear physics, **nuclear fusion** is a nuclear reaction in which two or more atomic nuclei come very close and then collide at a very high speed and join to form a new type of atomic nucleus. During this process, matter is not conserved because some of the matter of the fusing nuclei is converted to photons (energy). Fusion is the process that powers active or "main sequence" stars.

The fusion of two nuclei with lower masses than iron (which, along with nickel, has the largest binding energy per nucleon) generally releases energy, while the fusion of nuclei heavier than iron *absorbs* energy. The opposite is true for the reverse process, nuclear fission. This means that fusion generally occurs for lighter elements only, and likewise, that fission normally occurs only for heavier elements. There are extreme astrophysical events that can lead to short periods of fusion with heavier nuclei. This is the process that gives rise to nucleosynthesis, the creation of the heavy elements during events such as supernova.

Following the discovery of quantum tunneling by Friedrich Hund, in 1929 Robert Atkinson and Fritz Houtermans used the measured masses of light elements to predict that large amounts of energy could be released by fusing small nuclei. Building upon the nuclear transmutation experiments by Ernest Rutherford, carried out several years earlier, the laboratory fusion of hydrogen isotopes was first accomplished by Mark Oliphant in 1932. During the remainder of that decade the steps of the main cycle of nuclear fusion in stars were worked out by Hans Bethe. Research into fusion for military purposes began in the early 1940s as part of the Manhattan Project. Fusion was accomplished in 1951 with the Greenhouse Item nuclear test. Nuclear fusion on a large scale in an explosion was first carried out on November 1, 1952, in the Ivy Mike hydrogen bomb test.

Research into developing controlled thermonuclear fusion for civil purposes also began in earnest in the 1950s, and it continues to this day. The present article is about the theory of fusion. For details of the quest for controlled fusion and its history, see the article Fusion power.

**Process**



Fusion of deuterium with tritium creating helium-4, freeing a neutron, and releasing 17.59 MeV of energy, as an appropriate amount of mass changing forms to appear as the kinetic energy of the products, in agreement with *kinetic E* = Δ*mc*2, where *Δ*m is the change in rest mass of particles.

The origin of the energy released in fusion of light elements is due to interplay of two opposing forces, the nuclear force which combines together protons and neutrons, and the Coulomb force which causes protons to repel each other. The protons are positively charged and repel each other but they nonetheless stick together, demonstrating the existence of another force referred to as nuclear attraction. This force, called the strong nuclear force, overcomes electric repulsion in a very close range. The effect of this force is not observed outside the nucleus; hence the force has a strong dependence on distance, making it a short-range force. The same force also pulls the nucleons together, or neutrons and protons together. Because the nuclear force is stronger than the Coulomb force for atomic nuclei smaller than iron and nickel, building up these nuclei from lighter nuclei by **fusion** releases the extra energy from the net attraction of these particles. For larger nuclei, however, no energy is released, since the nuclear force is short-range and cannot continue to act across still larger atomic nuclei. Thus, energy is no longer released when such nuclei are made by fusion; instead, energy is absorbed in such processes.

Fusion reactions of light elements power the stars and produce virtually all elements in a process called nucleosynthesis. The fusion of lighter elements in stars releases energy (and the mass that always accompanies it). For example, in the fusion of two hydrogen nuclei to form helium, 0.7% of the mass is carried away from the system in the form of kinetic energy or other forms of energy (such as electromagnetic radiation).

Research into controlled fusion, with the aim of producing fusion power for the production of electricity, has been conducted for over 60 years. It has been accompanied by extreme scientific and technological difficulties, but has resulted in progress. At present, controlled fusion reactions have been unable to produce break-even (self-sustaining) controlled fusion reactions. Workable designs for a reactor that theoretically will deliver ten times more fusion energy than the amount needed to heat up plasma to required temperatures are in development (see ITER). The ITER facility is expected to finish its construction phase in 2019. It will start commissioning the reactor that same year and initiate plasma experiments in 2020, but is not expected to begin full deuterium-tritium fusion until 2027.

It takes considerable energy to force nuclei to fuse, even those of the lightest element, hydrogen. This is because all nuclei have a positive charge due to their protons, and as like charges repel, nuclei strongly resist being put close together. Accelerated to high speeds, they can overcome this electrostatic repulsion and be forced close enough for the attractive nuclear force to be sufficiently strong to achieve fusion. The fusion of lighter nuclei, which creates a heavier nucleus and often a free neutron or proton, generally releases more energy than it takes to force the nuclei together; this is an exothermic process that can produce self-sustaining reactions. The US National Ignition Facility, which uses laser-driven inertial confinement fusion, is thought to be capable of break-even fusion.

The first large-scale laser target experiments were performed in June 2009 and ignition experiments began in early 2011.

Energy released in most nuclear reactions is much larger than in chemical reactions, because the binding energy that holds a nucleus together is far greater than the energy that holds electrons to a nucleus. For example, the ionization energy gained by adding an electron to a hydrogen nucleus is 6982217896002232000♠13.6 eV—less than one-millionth of the 6988281983061712000♠17.6 MeV released in the deuterium–tritium (D–T) reaction shown in the diagram to the right (one gram of matter would release 7011339000000000000♠339 GJ of energy). Fusion reactions have an energy density many times greater than nuclear fission; the reactions produce far greater energy per unit of mass even though *individual* fission reactions are generally much more energetic than *individual* fusion ones, which are themselves millions of times more energetic than chemical reactions. Only direct conversion of mass into energy, such as that caused by the annihilator collision of matter and antimatter, is more energetic per unit of mass than nuclear fusion.

**Nuclear fusion in stars**



The proton-proton chain dominates in stars the size of the Sun or smaller.



The CNO cycle dominates in stars heavier than the Sun.

The most important fusion process in nature is the one that powers stars. 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. The fusion of nuclei in a star, starting from its initial hydrogen and helium abundance, provides that energy and synthesizes new nuclei as a byproduct of that fusion process. 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. Different reaction chains are involved, depending on the mass of the star. For stars the size of the sun or smaller, the proton-proton chain dominates. In heavier stars, the CNO cycle is more important.

As a star uses up a substantial fraction of its hydrogen, it begins to synthesize heavier elements, as part of stellar nucleosynthesis. 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.

**Requirements**

Details and supporting references on the material in this section can be found in textbooks on nuclear physics or nuclear fusion.

A substantial energy barrier of electrostatic forces must be overcome before fusion can occur. At large distances, two naked nuclei repel one another because of the repulsive electrostatic force between their positively charged protons. If two nuclei can be brought close enough together, however, the electrostatic repulsion can be overcome by the attractive nuclear force, which is stronger at close distances.

When a nucleon such as a proton or neutron is added to a nucleus, the nuclear force attracts it to other nucleons, but primarily to its immediate neighbors due to the short range of the force. The nucleons in the interior of a nucleus have more neighboring nucleons than those on the surface. Since smaller nuclei have a larger surface area-to-volume ratio, the binding energy per nucleon due to the nuclear force generally increases with the size of the nucleus but approaches a limiting value corresponding to that of a nucleus with a diameter of about four nucleons. It is important to keep in mind that the above picture is a toy model because nucleons are quantum objects, and so, for example, since two neutrons in a nucleus are identical to each other, distinguishing one from the other, such as which one is in the interior and which is on the surface, is in fact meaningless, and the inclusion of quantum mechanics is necessary for proper calculations.

The electrostatic force, on the other hand, is an inverse-square force, so a proton added to a nucleus will feel an electrostatic repulsion from *all* the other protons in the nucleus. The electrostatic energy per nucleon due to the electrostatic force thus increases without limit as nuclei get larger.



The electrostatic force between the positively charged nuclei is repulsive, but when the separation is small enough, the attractive nuclear force is stronger. Therefore, the prerequisite for fusion is that the nuclei have enough kinetic energy that they can approach each other despite the electrostatic repulsion.

The net result of these opposing forces is that the binding energy per nucleon generally increases with increasing size, up to the elements iron and nickel, and then decreases for heavier nuclei. Eventually, the binding energy becomes negative and very heavy nuclei (all with more than 208 nucleons, corresponding to a diameter of about 6 nucleons) are not stable. The four most tightly bound nuclei, in decreasing order of binding energy per nucleon, are 62Ni, 58Fe, 56Fe, and 60Ni. Even though the nickel isotope, 62Ni, is more stable, the iron isotope 56Fe is an order of magnitude more common. This is due to the fact that there is no easy way for stars to create 62Ni through the alpha process.

An exception to this general trend is the helium-4 nucleus, whose binding energy is higher than that of lithium, the next heaviest element. This is because protons and neutrons are fermions, which according to the Pauli exclusion principle cannot exist in the same nucleus in exactly the same state. Each proton or neutron energy state in a nucleus can accommodate both a spin up particle and a spin down particle. Helium-4 has an anomalously large binding energy because its nucleus consists of two protons and two neutrons, so all four of its nucleons can be in the ground state. Any additional nucleons would have to go into higher energy states. Indeed, the helium-4 nucleus is so tightly bound that it is commonly treated as a single particle in nuclear physics, namely, the alpha particle.

The situation is similar if two nuclei are brought together. As they approach each other, all the protons in one nucleus repel all the protons in the other. Not until the two nuclei actually come in contact can the strong nuclear force take over. Consequently, even when the final energy state is lower, there is a large energy barrier that must first be overcome. It is called the Coulomb barrier.

The Coulomb barrier is smallest for isotopes of hydrogen, as their nuclei contain only a single positive charge. A diproton is not stable, so neutrons must also be involved, ideally in such a way that a helium nucleus, with its extremely tight binding, is one of the products.

Using deuterium-tritium fuel, the resulting energy barrier is about 0.1 MeV. In comparison, the energy needed to remove an electron from hydrogen is 13.6 eV, about 7500 times less energy. The (intermediate) result of the fusion is an unstable 5He nucleus, which immediately ejects a neutron with 14.1 MeV. The recoil energy of the remaining 4He nucleus is 3.5 MeV, so the total energy liberated is 17.6 MeV. This is many times more than what was needed to overcome the energy barrier.



The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off. The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvin) and at a higher value than other reactions commonly considered for fusion energy.

The reaction **cross section** σ is a measure of the probability of a fusion reaction as a function of the relative velocity of the two reactant nuclei. If the reactants have a distribution of velocities, e.g. a thermal distribution, then it is useful to perform an average over the distributions of the product of cross section and velocity. This average is called the 'reactivity', denoted <σv>. The reaction rate (fusions per volume per time) is <σv> times the product of the reactant number densities:



If a species of nuclei is reacting with itself, such as the DD reaction, then the product must be replaced by .

increases from virtually zero at room temperatures up to meaningful magnitudes at temperatures of 10–100 keV. At these temperatures, well above typical ionization energies (13.6 eV in the hydrogen case), the fusion reactants exist in a plasma state.

The significance of as a function of temperature in a device with a particular energy confinement time is found by considering the Lawson criterion. This is an extremely challenging barrier to overcome on Earth, which explains why fusion research has taken many years to reach the current high state of technical prowess.

**Methods for achieving fusion**

Main article: Fusion power

**Thermonuclear fusion**

Main article: Thermonuclear fusion

If the matter is sufficiently heated (hence being plasma), the fusion reaction may occur due to collisions with extreme thermal kinetic energies of the particles. In the form of thermonuclear weapons, thermonuclear fusion is the only fusion technique so far to yield undeniably large amounts of useful fusion energy. Usable amounts of thermonuclear fusion energy released in a controlled manner have yet to be achieved. In nature, this is what produces energy in stars through stellar nucleosynthesis.

**Inertial confinement fusion**

Main article: Inertial confinement fusion

Inertial confinement fusion (**ICF**) is a type of fusion energy research that attempts to initiate nuclear fusion reactions by heating and compressing a fuel target, typically in the form of a pellet that most often contains a mixture of deuterium and tritium.

**Inertial electrostatic confinement**

Main article: Inertial electrostatic confinement

Inertial electrostatic confinement is a set of devices that use an electric field to heat ions to fusion conditions. The most well-known is the fusor. Starting in 1999, a number of amateurs have been able to do amateur fusion using these homemade devices. Other IEC devices include: the Polywell, MIX POPS and Marble concepts.

**Beam-beam or beam-target fusion**

If the energy to initiate the reaction comes from accelerating one of the nuclei, the process is called *beam-target* fusion; if both nuclei are accelerated, it is *beam-beam* fusion.

Accelerator-based light-ion fusion is a technique using particle accelerators to achieve particle kinetic energies sufficient to induce light-ion fusion reactions. Accelerating light ions is relatively easy, and can be done in an efficient manner—all it takes is a vacuum tube, a pair of electrodes, and a high-voltage transformer; fusion can be observed with as little as 10 kV between electrodes. The key problem with accelerator-based fusion (and with cold targets in general) is that fusion cross sections are many orders of magnitude lower than Coulomb interaction cross sections. Therefore the vast majority of ions end up expending their energy on bremsstrahlung and ionization of atoms of the target. Devices referred to as sealed-tube neutron generators are particularly relevant to this discussion. These small devices are miniature particle accelerators filled with deuterium and tritium gas in an arrangement that allows ions of these nuclei to be accelerated against hydride targets, also containing deuterium and tritium, where fusion takes place. Hundreds of neutron generators are produced annually for use in the petroleum industry where they are used in measurement equipment for locating and mapping oil reserves.

**Muon-catalyzed fusion**

Muon-catalyzed fusion is a well-established and reproducible fusion process that occurs at ordinary temperatures. It was studied in detail by Steven Jones in the early 1980s. Net energy production from this reaction cannot occur because of the high energy required to create muons, their short 2.2 µs half-life, and the high chance that a muon will bind to the new alpha particle and thus stop catalyzing fusion.

**Other principles**



The *Tokamak à configuration variable*, research fusion reactor, at the École Polytechnique Fédérale de Lausanne (Switzerland).

Some other confinement principles have been investigated.

Antimatter-initialized fusion uses small amounts of antimatter to trigger a tiny fusion explosion. This has been studied primarily in the context of making nuclear pulse propulsion, and pure fusion bombs feasible. This is not near becoming a practical power source, due to the cost of manufacturing antimatter alone.

Pyroelectric fusion was reported in April 2005 by a team at UCLA. The scientists used a pyroelectric crystal heated from −34 to 7 °C (−29 to 45 °F), combined with a tungsten needle to produce an electric field of about 25 gigavolts per meter to ionize and accelerate deuterium nuclei into an erbium deuteride target. At the estimated energy levels, the D-D fusion reaction may occur, producing helium-3 and a 2.45 MeV neutron. Although it makes a useful neutron generator, the apparatus is not intended for power generation since it requires far more energy than it produces.

Hybrid nuclear fusion-fission (hybrid nuclear power) is a proposed means of generating power by use of a combination of nuclear fusion and fission processes. The concept dates to the 1950s, and was briefly advocated by Hans Bethe during the 1970s, but largely remained unexplored until a revival of interest in 2009, due to the delays in the realization of pure fusion. Project PACER, carried out at Los Alamos National Laboratory (LANL) in the mid-1970s, explored the possibility of a fusion power system that would involve exploding small hydrogen bombs (fusion bombs) inside an underground cavity. As an energy source, the system is the only fusion power system that could be demonstrated to work using existing technology. However it would also require a large, continuous supply of nuclear bombs, making the economics of such a system rather questionable.

**Important reactions**

**Astrophysical reaction chains**

At the temperatures and densities in stellar cores the rates of fusion reactions are notoriously slow. For example, at solar core temperature (*T* ≈ 15 MK) and density (160 g/cm3), the energy release rate is only 276 μW/cm3—about a quarter of the volumetric rate at which a resting human body generates heat. Thus, reproduction of stellar core conditions in a lab for nuclear fusion power production is completely impractical. Because nuclear reaction rates strongly depend on temperature (exp(−*E*/*kT*)), achieving reasonable power levels in terrestrial fusion reactors requires 10–100 times higher temperatures (compared to stellar interiors): *T* ≈ 0.1–1.0 GK.

**Criteria and candidates for terrestrial reactions**

Main article: Fusion power § Fuels

In artificial fusion, the primary fuel is not constrained to be protons and higher temperatures can be used, so reactions with larger cross-sections are chosen. Another concern is the production of neutrons, which activate the reactor structure radiologically, but also have the advantages of allowing volumetric extraction of the fusion energy and tritium breeding. Reactions that release no neutrons are referred to as *aneutronic*.

To be a useful energy source, a fusion reaction must satisfy several criteria. It must:

* **Be** exothermic: This limits the reactants to the low *Z* (number of protons) side of the curve of binding energy. It also makes helium 4He the most common product because of its extraordinarily tight binding, although 3He and 3H also show up.
* **Involve low *Z* nuclei**: This is because the electrostatic repulsion must be overcome before the nuclei are close enough to fuse.
* **Have two reactants**: At anything less than stellar densities, three body collisions are too improbable. In inertial confinement, both stellar densities and temperatures are exceeded to compensate for the shortcomings of the third parameter of the Lawson criterion, ICF's very short confinement time.
* **Have two or more products**: This allows simultaneous conservation of energy and momentum without relying on the electromagnetic force.
* **Conserve both protons and neutrons**: The cross sections for the weak interaction are too small.

Few reactions meet these criteria. The following are those with the largest cross sections:

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| (1)  | 21D  | +  | 31T  | →  | 42He  | (  | 3.5 MeV  | )  | +  | n0  | (  | 14.1 MeV  | ) |
| (2i)  | 21D  | +  | 21D  | →  | 31T  | (  | 1.01 MeV  | )  | +  | p+  | (  | 3.02 MeV  | )  |  |  |  |  |  | 50% |
| (2ii)  |  |  |  | →  | 32He  | (  | 0.82 MeV  | )  | +  | n0  | (  | 2.45 MeV  | )  |  |  |  |  |  | 50% |
| (3)  | 21D  | +  | 32He  | →  | 42He  | (  | 3.6 MeV  | )  | +  | p+  | (  | 14.7 MeV  | ) |  |  |  |  |  |  |
| (4)  | 31T  | +  | 31T  | →  | 42He  |  |  |  | +  | 2 n0  |  |  |  |  |  | +  | 11.3 MeV |  |  |
| (5)  | 32He  | +  | 32He  | →  | 42He  |  |  |  | +  | 2 p+  |  |  |  |  |  | +  | 12.9 MeV |  |  |
| (6i)  | 32He  | +  | 31T  | →  | 42He  |  |  |  | +  | p+  | +  | n0  |  |  |  | +  | 12.1 MeV  |  | 57% |
| (6ii)  |  |  |  | →  | 42He  | (  | 4.8 MeV  | )  | +  | 21D  | (  | 9.5 MeV  | )  |  |  |  |  |  | 43% |
| (7i)  | 21D  | +  | 63Li  | →  | 2 42He  | +  | 22.4 MeV |  |  |  |  |  |  |  |  |  |  |  |  |
| (7ii)  |  |  |  | →  | 32He  | +  | 42He  |  | +  | n0  |  |  |  |  |  | +  | 2.56 MeV |  |  |
| (7iii)  |  |  |  | →  | 73Li  | +  | p+  |  |  |  |  |  |  |  |  | +  | 5.0 MeV |  |  |
| (7iv)  |  |  |  | →  | 74Be  | +  | n0  |  |  |  |  |  |  |  |  | +  | 3.4 MeV |  |  |
| (8)  | p+  | +  | 63Li  | →  | 42He  | (  | 1.7 MeV  | )  | +  | 32He  | (  | 2.3 MeV  | ) |  |  |  |  |  |  |
| (9)  | 32He  | +  | 63Li  | →  | 2 42He  | +  | p+  |  |  |  |  |  |  |  |  | +  | 16.9 MeV |  |  |
| (10)  | p+  | +  | 115B  | →  | 3 42He  |  |  |  |  |  |  |  |  |  |  | +  | 8.7 MeV |  |  |

|  |
| --- |
| **Nucleosynthesis** |
|  |
| * Stellar nucleosynthesis
* Big Bang nucleosynthesis
* Supernova nucleosynthesis
* Cosmic ray spallation
 |
| **Related topics** |
| * Astrophysics
* **Nuclear fusion**
	+ R-process
	+ S-process
* Nuclear fission
 |
|  |

For reactions with two products, the energy is divided between them in inverse proportion to their masses, as shown. In most reactions with three products, the distribution of energy varies. For reactions that can result in more than one set of products, the branching ratios are given.

Some reaction candidates can be eliminated at once. The D-6Li reaction has no advantage compared to p+-11
5B because it is roughly as difficult to burn but produces substantially more neutrons through 2
1D-2
1D side reactions. There is also a p+-7
3Li reaction, but the cross section is far too low, except possibly when *T*i > 1 MeV, but at such high temperatures an endothermic, direct neutron-producing reaction also becomes very significant. Finally there is also a p+-9
4Be reaction, which is not only difficult to burn, but 9
4Be can be easily induced to split into two alpha particles and a neutron.

In addition to the fusion reactions, the following reactions with neutrons are important in order to "breed" tritium in "dry" fusion bombs and some proposed fusion reactors:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| n0  | +  | 63Li  | →  | 31T  | +  | 42He + 4.784 MeV |
| n0  | +  | 73Li  | →  | 31T  | +  | 42He + n0 – 2.467 MeV |

The latter of the two equations was unknown when the U.S. conducted the Castle Bravo fusion bomb test in 1954. Being just the second fusion bomb ever tested (and the first to use lithium), the designers of the Castle Bravo "Shrimp" had understood the usefulness of Lithium-6 in tritium production, but had failed to recognize that Lithium-7 fission would greatly increase the yield of the bomb. While Li-7 has a small neutron cross-section for low neutron energies, it has a higher cross section above 5 MeV. Li-7 also undergoes a chain reaction due to its release of a neutron after fissioning. The 15 Mt yield was 150% greater than the predicted 6 Mt and caused casualties from the fallout generated.

To evaluate the usefulness of these reactions, in addition to the reactants, the products, and the energy released, one needs to know something about the cross section. Any given fusion device has a maximum plasma pressure it can sustain, and an economical device would always operate near this maximum. Given this pressure, the largest fusion output is obtained when the temperature is chosen so that <σv>/T2 is a maximum. This is also the temperature at which the value of the triple product *nT*τ required for ignition is a minimum, since that required value is inversely proportional to <σv>/T2 (see Lawson criterion). (A plasma is "ignited" if the fusion reactions produce enough power to maintain the temperature without external heating.) This optimum temperature and the value of <σv>/T2 at that temperature is given for a few of these reactions in the following table.

|  |  |  |
| --- | --- | --- |
| **fuel** | ***T* [keV]** | **<σv>/T2 [m3/s/keV2]** |
| 21D-31T | 13.6 | 1.24×10−24 |
| 21D-21D | 15 | 1.28×10−26 |
| 21D-32He | 58 | 2.24×10−26 |
| p+-63Li | 66 | 1.46×10−27 |
| p+-115B | 123 | 3.01×10−27 |

Note that many of the reactions form chains. For instance, a reactor fueled with 3
1T and 3
2He creates some 2
1D, which is then possible to use in the 2
1D-3
2He reaction if the energies are "right". An elegant idea is to combine the reactions (8) and (9). The 3
2He from reaction (8) can react with 6
3Li in reaction (9) before completely thermalizing. This produces an energetic proton, which in turn undergoes reaction (8) before thermalizing. Detailed analysis shows that this idea would not work well, but it is a good example of a case where the usual assumption of a Maxwellian plasma is not appropriate.

**Neutronicity, confinement requirement, and power density**



The only man-made fusion device to achieve ignition to date is the hydrogen bomb. The detonation of the first device, codenamed Ivy Mike, occurred in 1952 and is shown here.

Any of the reactions above can in principle be the basis of fusion power production. In addition to the temperature and cross section discussed above, we must consider the total energy of the fusion products *E*fus, the energy of the charged fusion products *E*ch, and the atomic number *Z* of the non-hydrogenic reactant.

Specification of the 2
1D-2
1D reaction entails some difficulties, though. To begin with, one must average over the two branches (2i) and (2ii). More difficult is to decide how to treat the 3
1T and 3
2He products. 3
1T burns so well in a deuterium plasma that it is almost impossible to extract from the plasma. The 2
1D-3
2He reaction is optimized at a much higher temperature, so the burnup at the optimum 2
1D-2
1D temperature may be low, so it seems reasonable to assume the 3
1T but not the 3
2He gets burned up and adds its energy to the net reaction. Thus the total reaction would be the sum of (2i), (2ii), and (1):

5 2
1D → 4
2He + 2 n0 + 3
2He + p+, *E*fus = 4.03+17.6+3.27 = 24.9 MeV, *E*ch = 4.03+3.5+0.82 = 8.35 MeV.

We count the 2
1D-2
1D fusion energy *per D-D reaction* (not per pair of deuterium atoms) as *E*fus = (4.03 MeV + 17.6 MeV)×50% + (3.27 MeV)×50% = 12.5 MeV and the energy in charged particles as *E*ch = (4.03 MeV + 3.5 MeV)×50% + (0.82 MeV)×50% = 4.2 MeV. (Note: if the tritium ion reacts with a deuteron while it still has a large kinetic energy, then the kinetic energy of the helium-4 produced may be quite different from 3.5 MeV, so this calculation of energy in charged particles is only approximate.)

Another unique aspect of the 2
1D-2
1D reaction is that there is only one reactant, which must be taken into account when calculating the reaction rate.

With this choice, we tabulate parameters for four of the most important reactions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **fuel** | ***Z*** | ***E*fus [MeV]** | ***E*ch [MeV]** | **neutronicity** |
| 21D-31T | 1 | 17.6 | 3.5 | 0.80 |
| 21D-21D | 1 | 12.5 | 4.2 | 0.66 |
| 21D-32He | 2 | 18.3 | 18.3 | ~0.05 |
| p+-115B | 5 | 8.7 | 8.7 | ~0.001 |

The last column is the neutronicity of the reaction, the fraction of the fusion energy released as neutrons. This is an important indicator of the magnitude of the problems associated with neutrons like radiation damage, biological shielding, remote handling, and safety. For the first two reactions it is calculated as (*E*fus-*E*ch)/*E*fus. For the last two reactions, where this calculation would give zero, the values quoted are rough estimates based on side reactions that produce neutrons in a plasma in thermal equilibrium.

Of course, the reactants should also be mixed in the optimal proportions. This is the case when each reactant ion plus its associated electrons accounts for half the pressure. Assuming that the total pressure is fixed, this means that density of the non-hydrogenic ion is smaller than that of the hydrogenic ion by a factor 2/(*Z*+1). Therefore the rate for these reactions is reduced by the same factor, on top of any differences in the values of <σv>/T2. On the other hand, because the 2
1D-2
1D reaction has only one reactant, its rate is twice as high as when the fuel is divided between two different hydrogenic species, thus creating a more efficient reaction.

Thus there is a "penalty" of (2/(Z+1)) for non-hydrogenic fuels arising from the fact that they require more electrons, which take up pressure without participating in the fusion reaction. (It is usually a good assumption that the electron temperature will be nearly equal to the ion temperature. Some authors, however discuss the possibility that the electrons could be maintained substantially colder than the ions. In such a case, known as a "hot ion mode", the "penalty" would not apply.) There is at the same time a "bonus" of a factor 2 for 2
1D-2
1D because each ion can react with any of the other ions, not just a fraction of them.

We can now compare these reactions in the following table.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **fuel** | **<σv>/T2** | **penalty/bonus** | **reactivity** | **Lawson criterion** | **power density (W/m3/kPa2)** | **relation of power density** |
| 21D-31T | 1.24×10−24 | 1 | 1 | 1 | 34 | 1 |
| 21D-21D | 1.28×10−26 | 2 | 48 | 30 | 0.5 | 68 |
| 21D-32He | 2.24×10−26 | 2/3 | 83 | 16 | 0.43 | 80 |
| p+-63Li | 1.46×10−27 | 1/2 | 1700 |  | 0.005 | 6800 |
| p+-115B | 3.01×10−27 | 1/3 | 1240 | 500 | 0.014 | 2500 |

The maximum value of <σv>/T2 is taken from a previous table. The "penalty/bonus" factor is that related to a non-hydrogenic reactant or a single-species reaction. The values in the column "reactivity" are found by dividing 1.24×10−24 by the product of the second and third columns. It indicates the factor by which the other reactions occur more slowly than the 21D-31T reaction under comparable conditions. The column "Lawson criterion" weights these results with *E*ch and gives an indication of how much more difficult it is to achieve ignition with these reactions, relative to the difficulty for the 21D-31T reaction. The last column is labeled "power density" and weights the practical reactivity with *E*fus. It indicates how much lower the fusion power density of the other reactions is compared to the 21D-31T reaction and can be considered a measure of the economic potential.

**Bremsstrahlung losses in quasineutral, isotropic plasmas**

The ions undergoing fusion in many systems will essentially never occur alone but will be mixed with electrons that in aggregate neutralize the ions' bulk electrical charge and form a plasma. The electrons will generally have a temperature comparable to or greater than that of the ions, so they will collide with the ions and emit x-ray radiation of 10–30 keV energy (Bremsstrahlung). The Sun and stars are opaque to x-rays, but essentially any terrestrial fusion reactor will be optically thin for x-rays of this energy range. X-rays are difficult to reflect but they are effectively absorbed (and converted into heat) in less than mm thickness of stainless steel (which is part of a reactor's shield). The ratio of fusion power produced to x-ray radiation lost to walls is an important figure of merit. This ratio is generally maximized at a much higher temperature than that which maximizes the power density (see the previous subsection). The following table shows estimates of the optimum temperature and the power ratio at that temperature for several reactions.

|  |  |  |
| --- | --- | --- |
| **fuel** | ***T*i (keV)** | ***P*fusion/*P*Bremsstrahlung** |
| 21D-31T | 50 | 140 |
| 21D-21D | 500 | 2.9 |
| 21D-32He | 100 | 5.3 |
| 32He-32He | 1000 | 0.72 |
| p+-63Li | 800 | 0.21 |
| p+-115B | 300 | 0.57 |

The actual ratios of fusion to Bremsstrahlung power will likely be significantly lower for several reasons. For one, the calculation assumes that the energy of the fusion products is transmitted completely to the fuel ions, which then lose energy to the electrons by collisions, which in turn lose energy by Bremsstrahlung. However, because the fusion products move much faster than the fuel ions, they will give up a significant fraction of their energy directly to the electrons. Secondly, the ions in the plasma are assumed to be purely fuel ions. In practice, there will be a significant proportion of impurity ions, which will then lower the ratio. In particular, the fusion products themselves *must* remain in the plasma until they have given up their energy, and *will* remain some time after that in any proposed confinement scheme. Finally, all channels of energy loss other than Bremsstrahlung have been neglected. The last two factors are related. On theoretical and experimental grounds, particle and energy confinement seem to be closely related. In a confinement scheme that does a good job of retaining energy, fusion products will build up. If the fusion products are efficiently ejected, then energy confinement will be poor, too.

The temperatures maximizing the fusion power compared to the Bremsstrahlung are in every case higher than the temperature that maximizes the power density and minimizes the required value of the fusion triple product. This will not change the optimum operating point for 21D-31T very much because the Bremsstrahlung fraction is low, but it will push the other fuels into regimes where the power density relative to 21D-31T is even lower and the required confinement even more difficult to achieve. For 21D-21D and 21D-32He, Bremsstrahlung losses will be a serious, possibly prohibitive problem. For 32He-32He, p+-63Li and p+-115 B the Bremsstrahlung losses appear to make a fusion reactor using these fuels with a quasineutral, isotropic plasma impossible. Some ways out of this dilemma are considered—and rejected—in *Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium* by Todd Rider. This limitation does not apply to non-neutral and anisotropic plasmas; however, these have their own challenges to contend with.