Fusion energy

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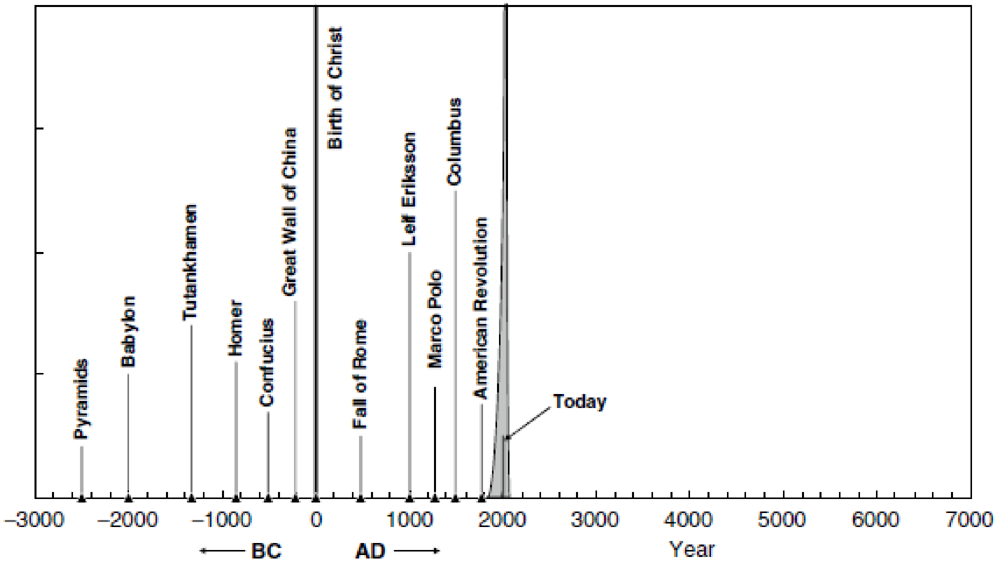
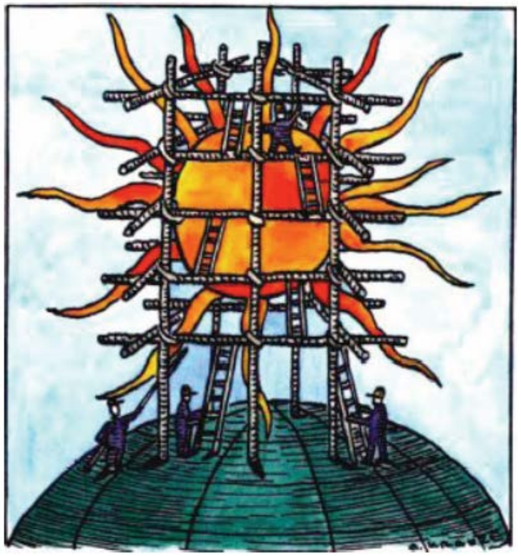
Toward sustainable world

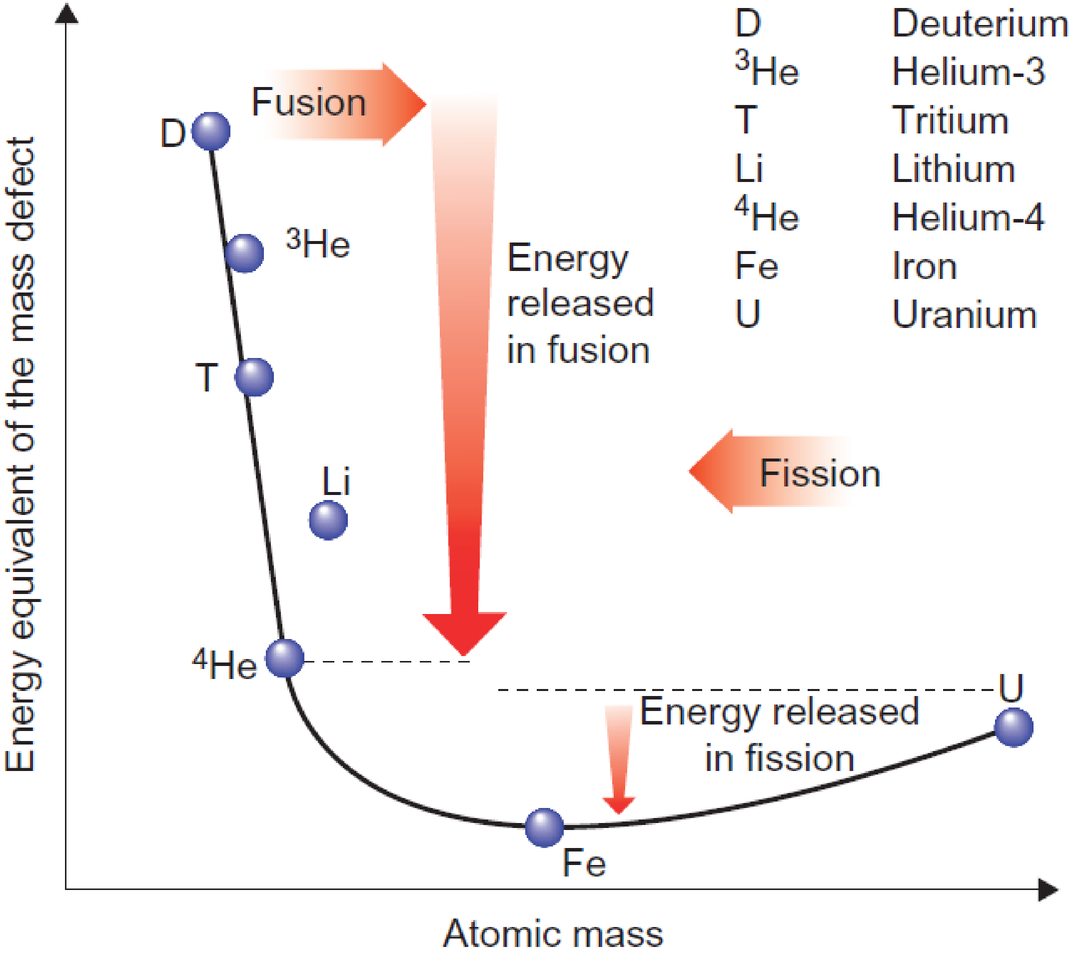
- Several hundred million years ago, light from the sun produced trees on the earth, and these were eventually converted into fossil fuels in the earth's crust. This legacy of easy energy allowed mankind to develop the advanced civilization that we enjoy today. But it is fast running out.
- The sun is the ultimate source of 90% of the energy we use, but it is mostly in fossil form. The everyday influx of solar power is too dilute to supply all energy that we use.
- Controlled nuclear fusion, or "fusion" for short, is about making an artificial sun on earth.





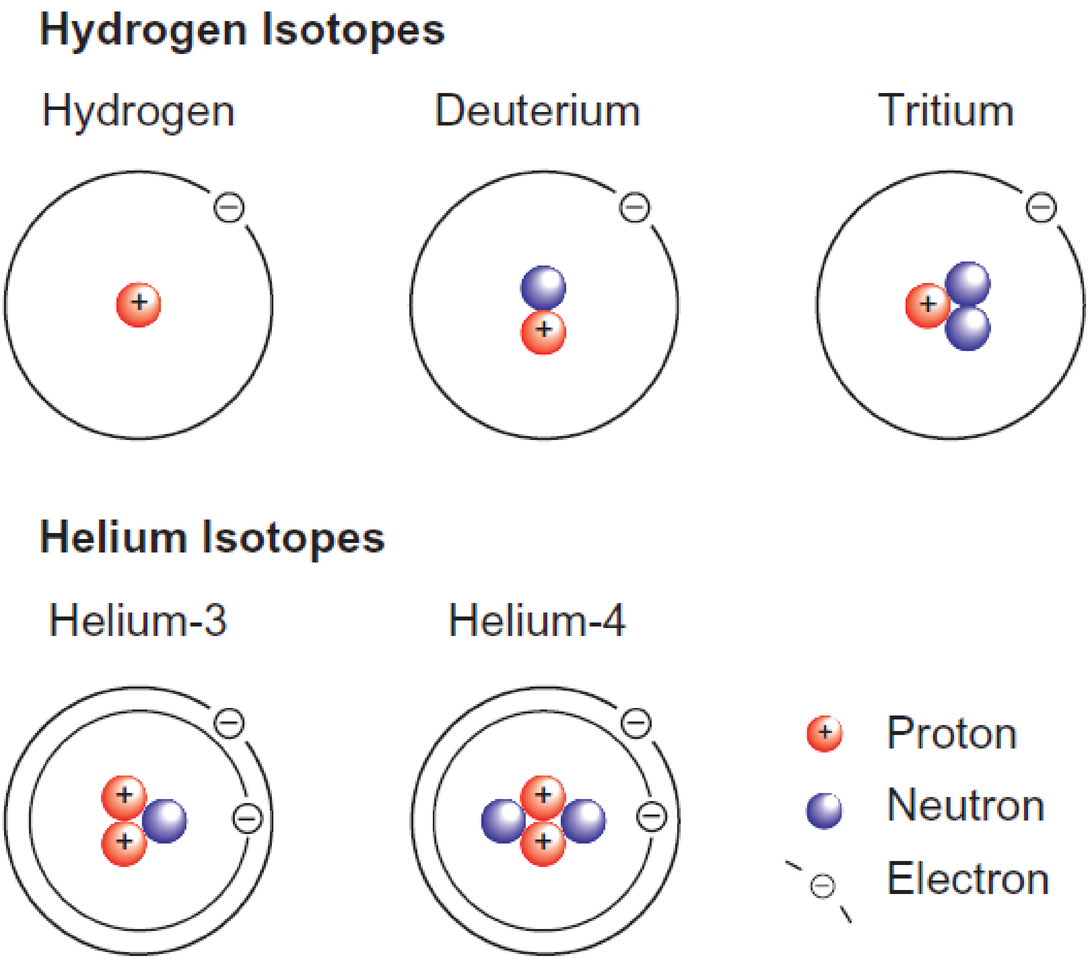
Energy from mass

- Albert Einstein said that “If a body gives off the energy E in the form of radiation, its mass diminishes by E/c^2.”



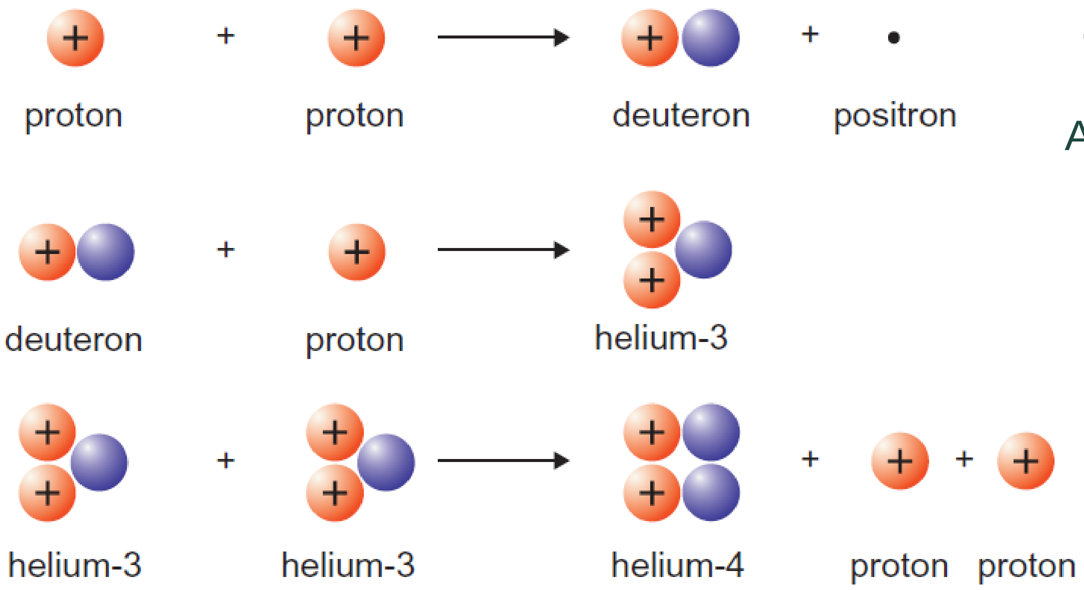
Isotopes used for nuclear fusion

- Atoms with the same number of protons and different numbers of neutrons are known as isotopes of the same element.



The Sun's energy

- Hydrogen and helium are by far the most common elements in the universe, and together they account for about 98% of all known matter.
- The energy release in the Sun involves the conversion of four protons into a helium nucleus.



→ Very slow (bottleneck)

Average lifetime of a proton in the core:

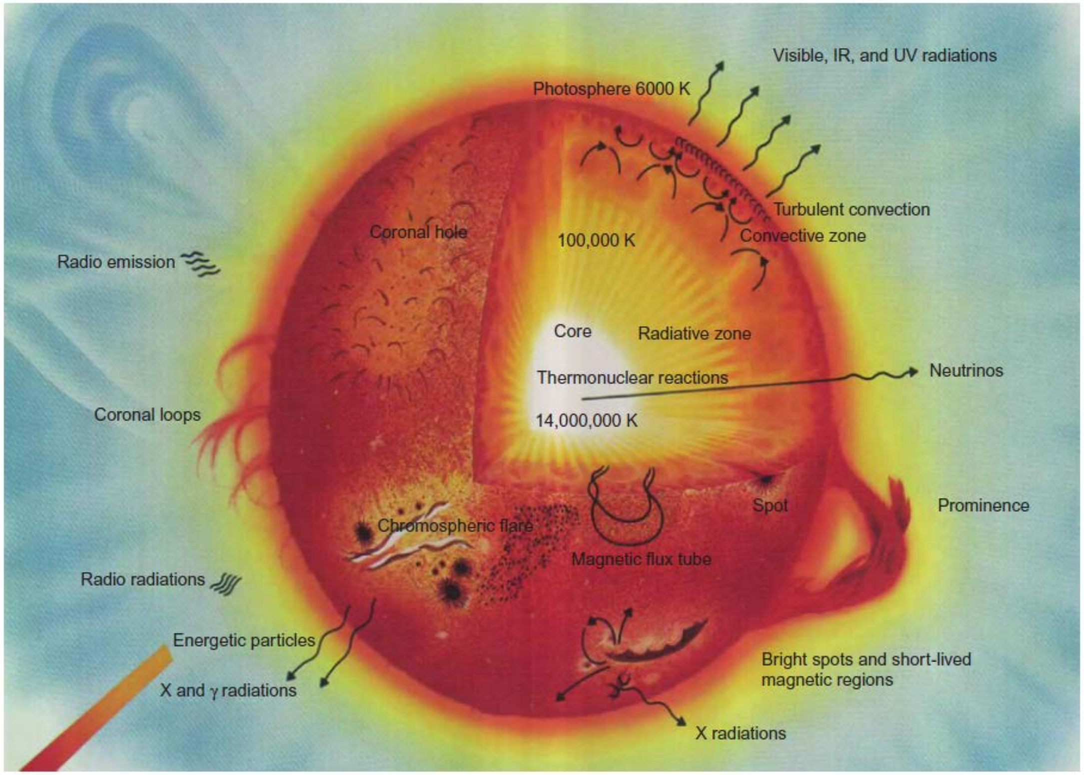
$$\tau = \frac{N_p}{R_{pp}} \approx \frac{10^{26}\ \mathrm{cm}^{-3}}{10^{8}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}} \approx 3 \times 10^{10}\ \mathrm{yr}$$

→ $4\ {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\gamma + 2\beta^{+} + 2\nu + 26.72\ \mathrm{MeV}$

- [H/W] Survey the star's life according to its mass in view of fusion reaction.

Gravitational confinement

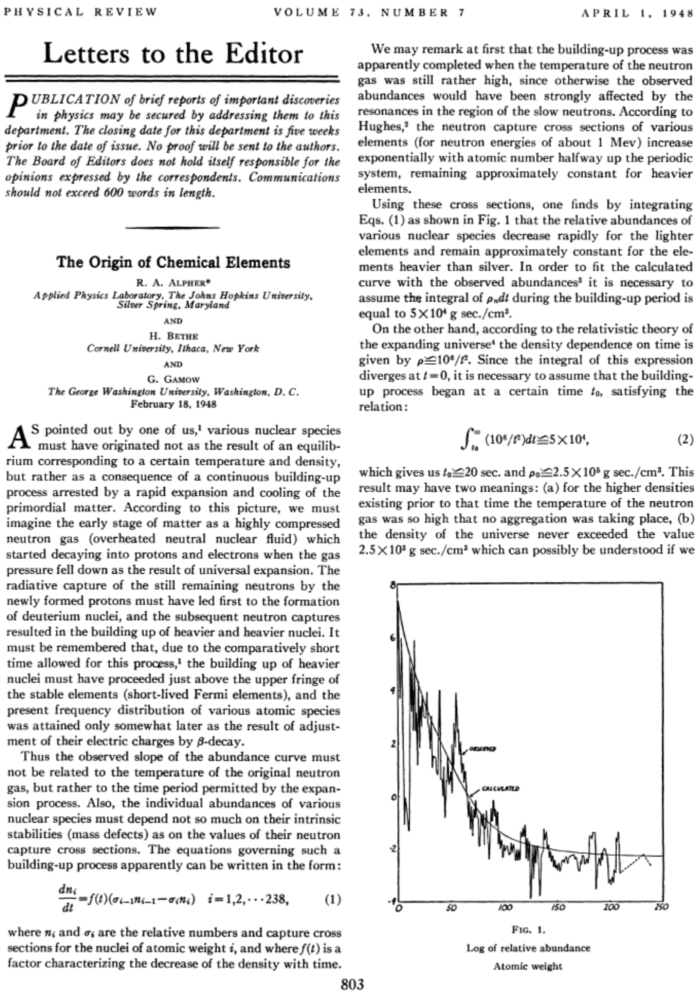
- The combination of high density and high temperature exerts an enormous outward pressure that is about 4×10^{11} bar. An inward force must balance this enormous outward pressure in order to prevent the Sun from expanding.
- Gravity provides this force in the Sun and stars, and it compresses the Sun into the most compact shape possible, a sphere.



Power density ~ 270 W/m^3
(Commercial reactor ~ MW/m^3)

Formation of heavier atoms

- Big Bang: an expanding universe model was described in detail by George Gamow, Ralph Alpher, and Hans Bethe in 1948 in their famous “$\alpha\beta\gamma$” paper.



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Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

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AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

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We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

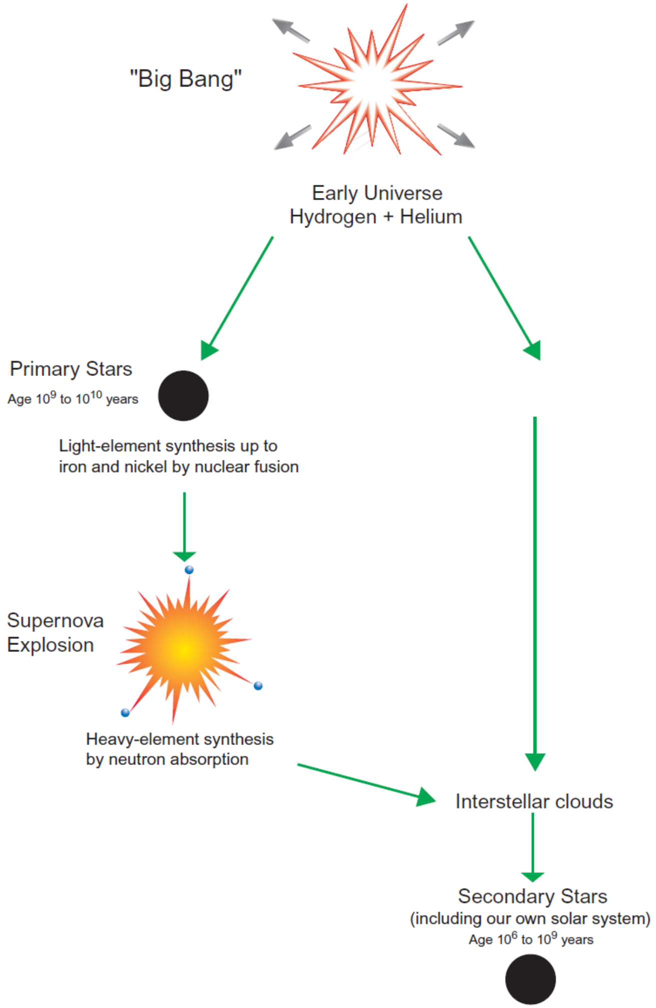
$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \qquad (2)$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

FIG. 1.

Log of relative abundance

Atomic weight



"Big Bang"

Early Universe
Hydrogen + Helium

Primary Stars
Age 10^9 to 10^{10} years

Light-element synthesis up to
iron and nickel by nuclear fusion

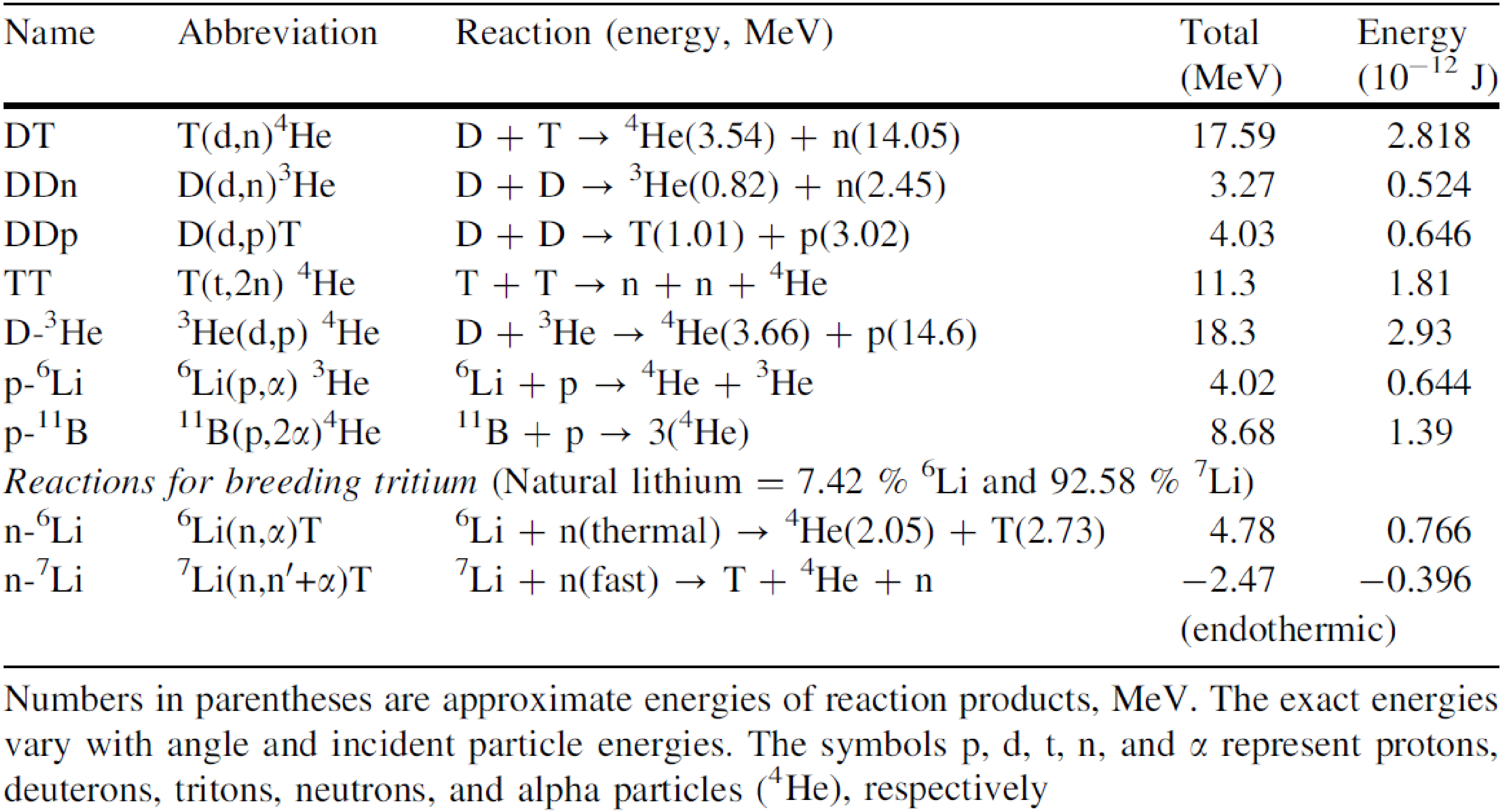
Supernova
Explosion

Heavy-element synthesis
by neutron absorption

Interstellar clouds

Secondary Stars
(including our own solar system)
Age 10^6 to 10^9 years

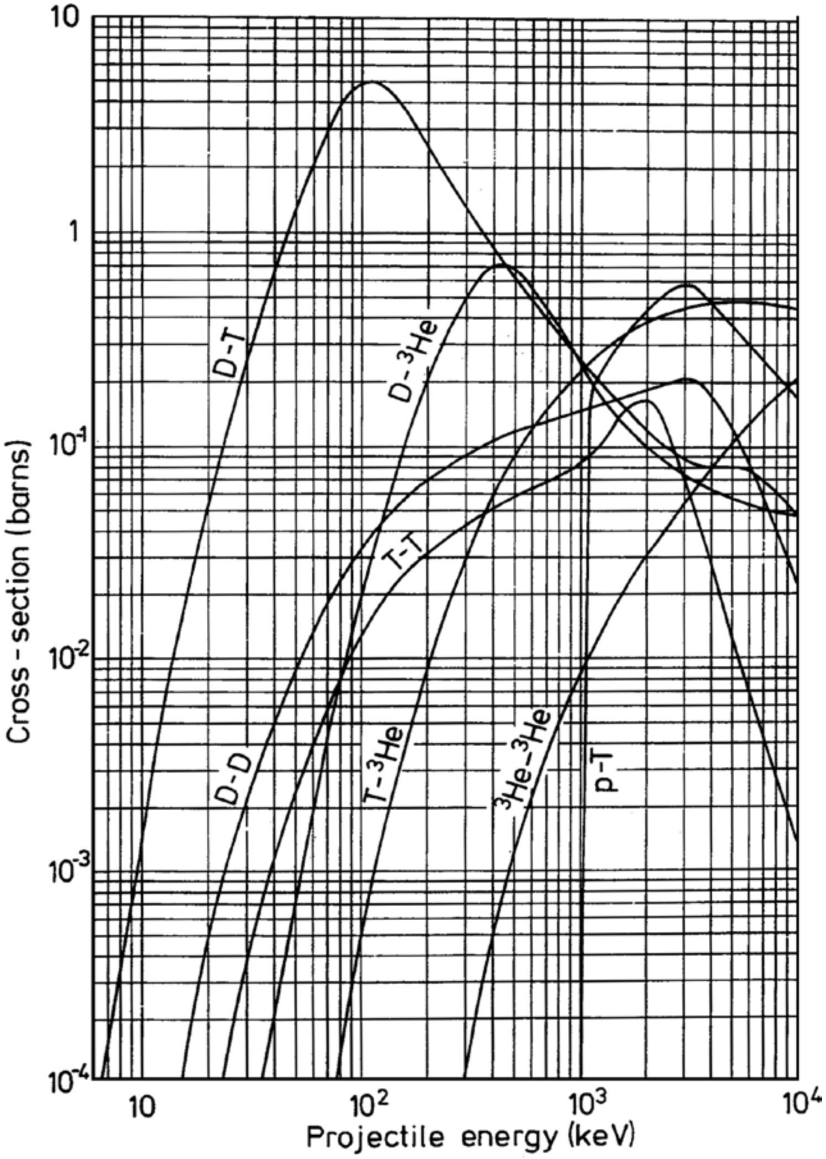
Nuclear fusion reactions of interest

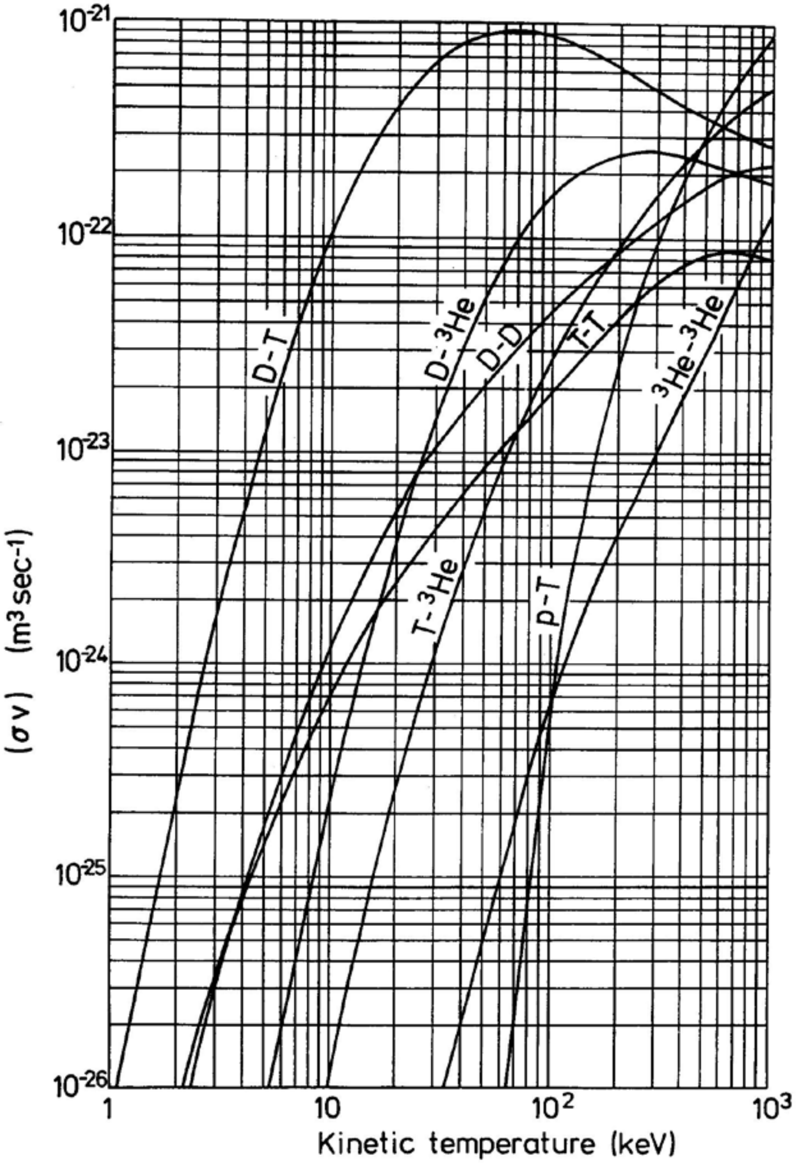


Name	Abbreviation	Reaction (energy, MeV)	Total (MeV)	Energy (10^{-12} J)
DT	$T(d,n)^4He$	$D + T \rightarrow {}^4He(3.54) + n(14.05)$	17.59	2.818
DDn	$D(d,n)^3He$	$D + D \rightarrow {}^3He(0.82) + n(2.45)$	3.27	0.524
DDp	$D(d,p)T$	$D + D \rightarrow T(1.01) + p(3.02)$	4.03	0.646
TT	$T(t,2n)\ {}^4He$	$T + T \rightarrow n + n + {}^4He$	11.3	1.81
D-^{3}He	$^3He(d,p)\ {}^4He$	$D + {}^3He \rightarrow {}^4He(3.66) + p(14.6)$	18.3	2.93
p-^{6}Li	$^6Li(p,\alpha)\ {}^3He$	$^6Li + p \rightarrow {}^4He + {}^3He$	4.02	0.644
p-^{11}B	$^{11}B(p,2\alpha)^4He$	$^{11}B + p \rightarrow 3({}^4He)$	8.68	1.39
Reactions for breeding tritium (Natural lithium = 7.42 % ^{6}Li and 92.58 % ^{7}Li)				
n-^{6}Li	$^6Li(n,\alpha)T$	$^6Li + n(\text{thermal}) \rightarrow {}^4He(2.05) + T(2.73)$	4.78	0.766
n-^{7}Li	$^7Li(n,n'+\alpha)T$	$^7Li + n(\text{fast}) \rightarrow T + {}^4He + n$	−2.47 (endothermic)	−0.396

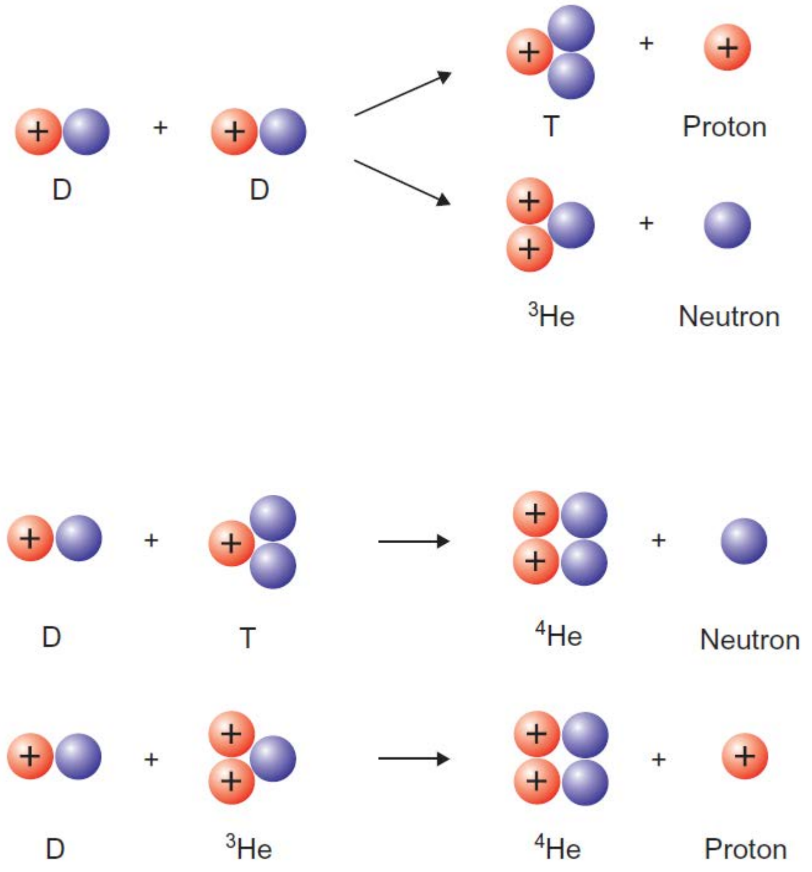
Numbers in parentheses are approximate energies of reaction products, MeV. The exact energies vary with angle and incident particle energies. The symbols p, d, t, n, and α represent protons, deuterons, tritons, neutrons, and alpha particles (^{4}He), respectively

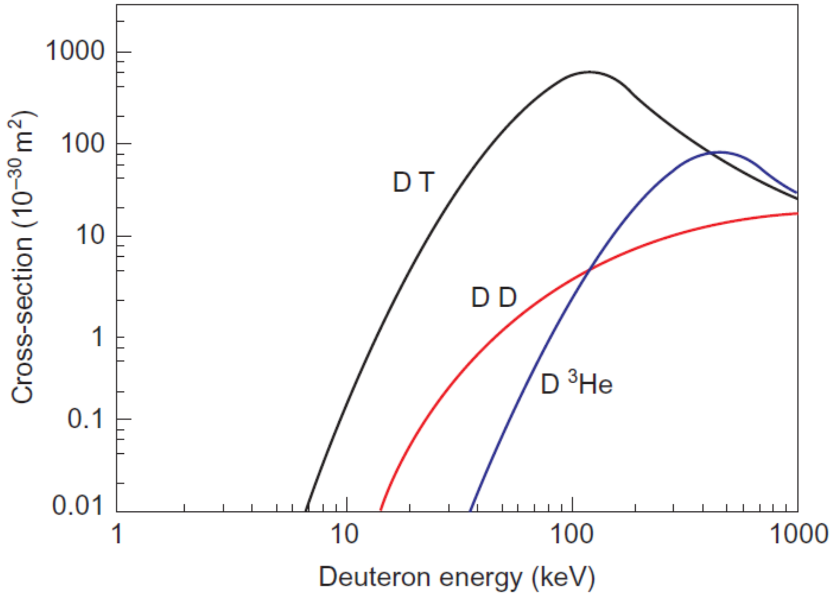
Fusion cross section data

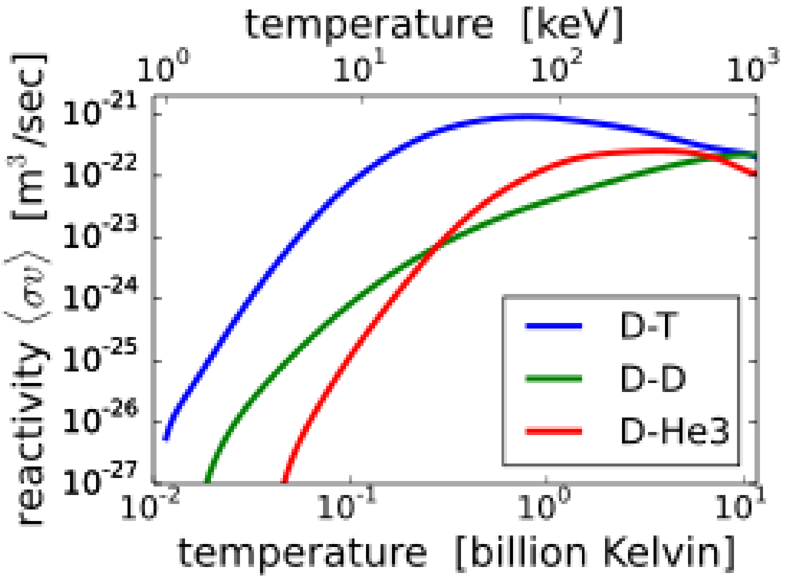




Three major fusion reactions

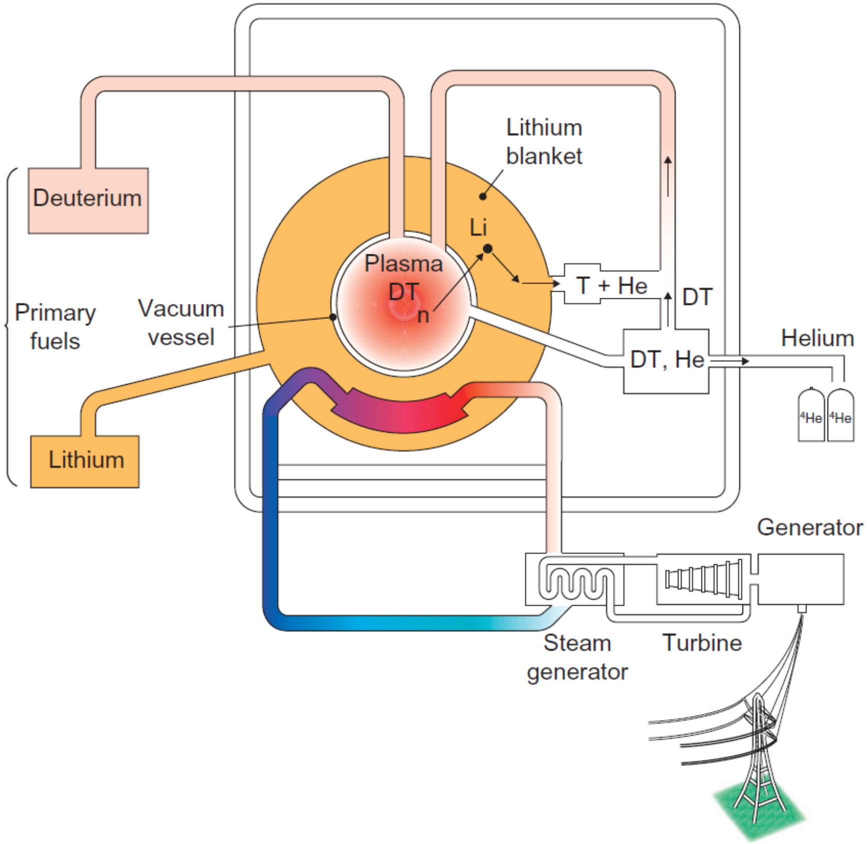






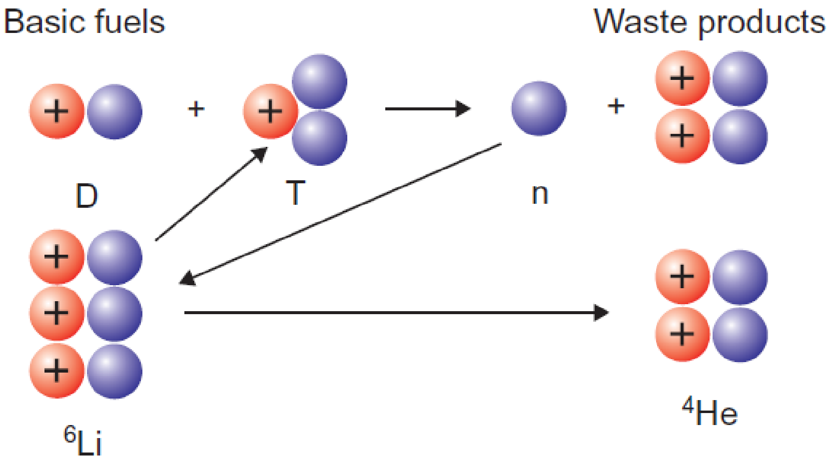
Schematic of man-made fusion reactor

- The most promising reaction is that between the two rare forms of hydrogen, called deuterium and tritium.
- Deuterium is present naturally in water and is therefore readily available. Tritium is not available naturally and has to be produced in situ in the power plant.



$$D + T \rightarrow \alpha(3.5\,\mathrm{MeV}) + n(14.1\,\mathrm{MeV})$$

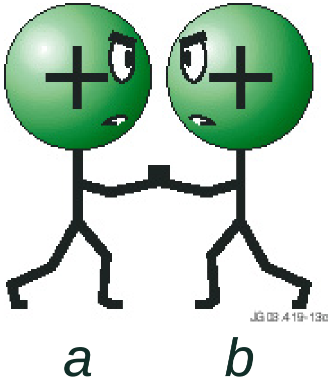
$$^6\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + 4.8\,\mathrm{MeV}$$
$$^7\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + \mathrm{n} - 2.5\,\mathrm{MeV}$$

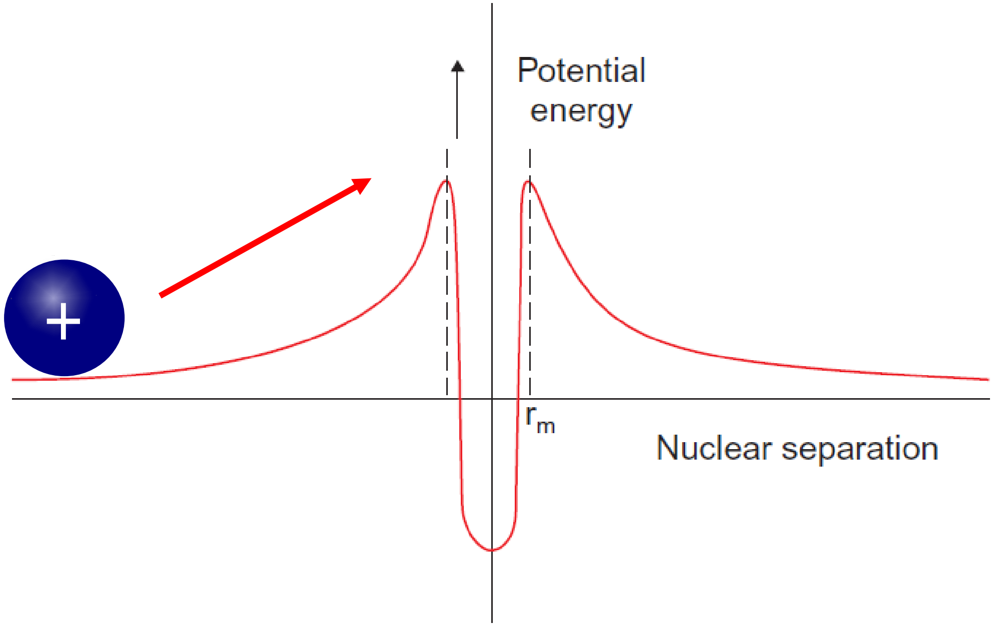


How fusion works

- In order to initiate these fusion reactions, two nuclei have to be brought very close together, to distances comparable to their size.
- The easiest way for fusion reactions to occur is bombarding accelerated deuterium nuclei (~100 keV) to a solid target containing tritium. → Beam-target fusion (only 1 in 100 million results in a fusion event)

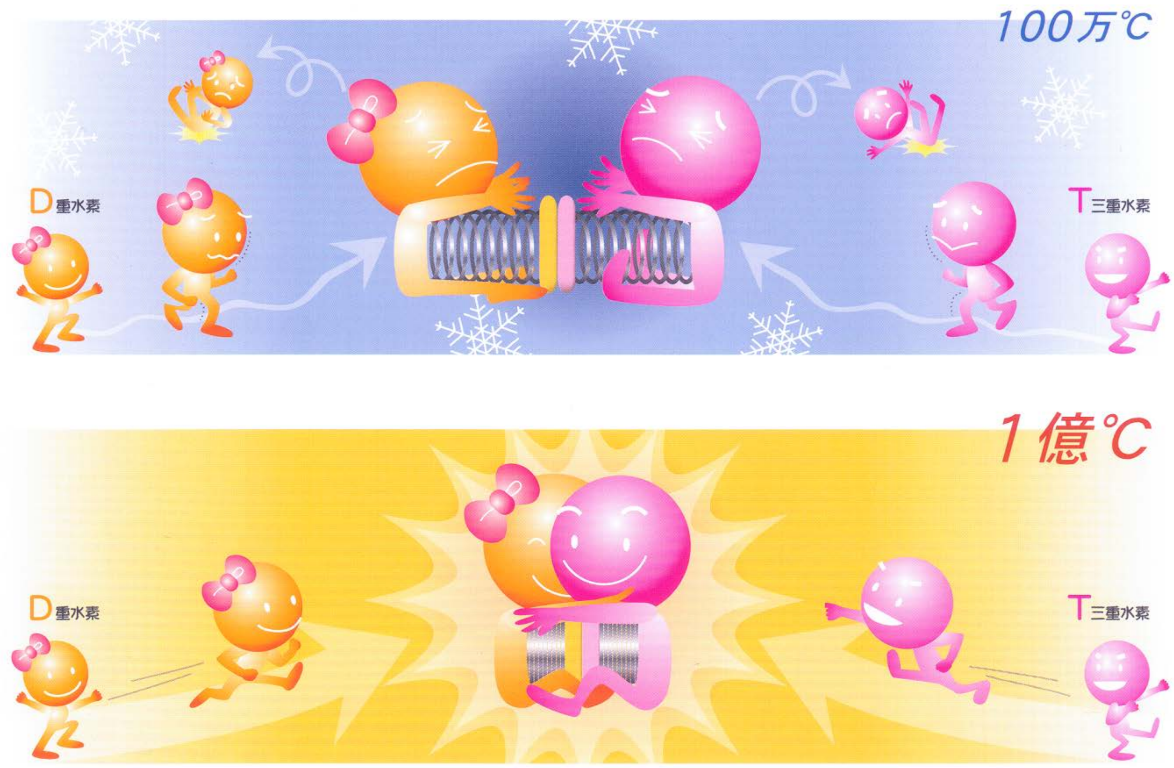
$$F_{c,a} = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{r^3}\vec{r}$$





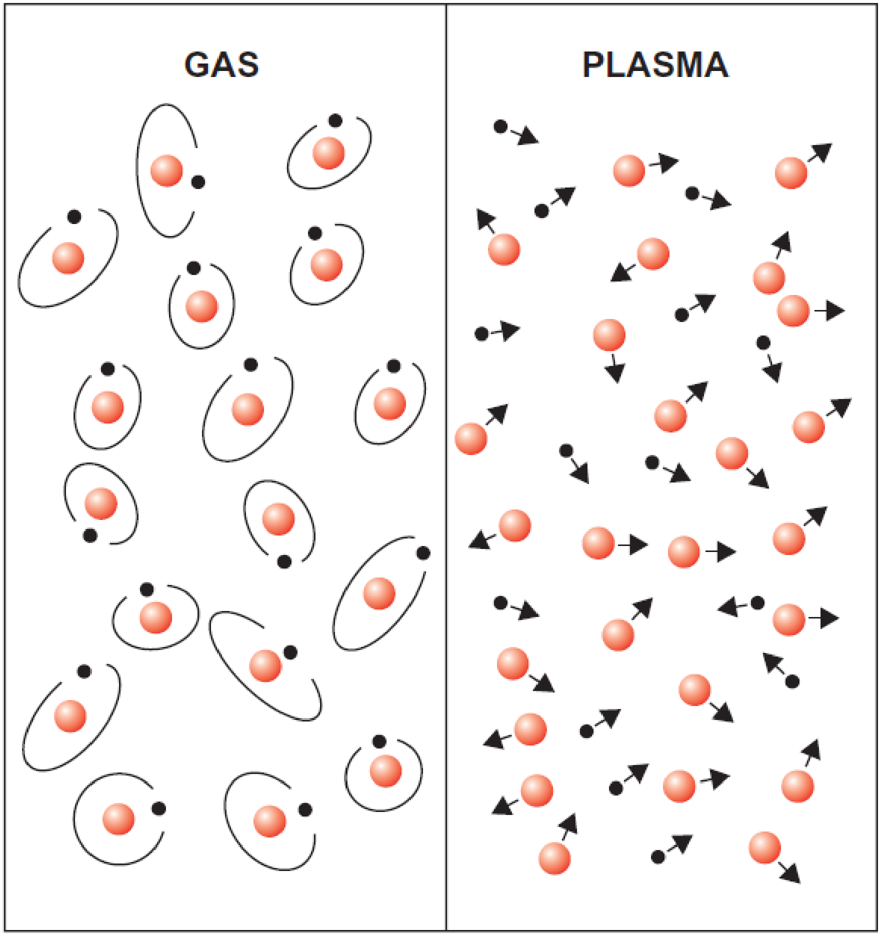
Thermonuclear fusion

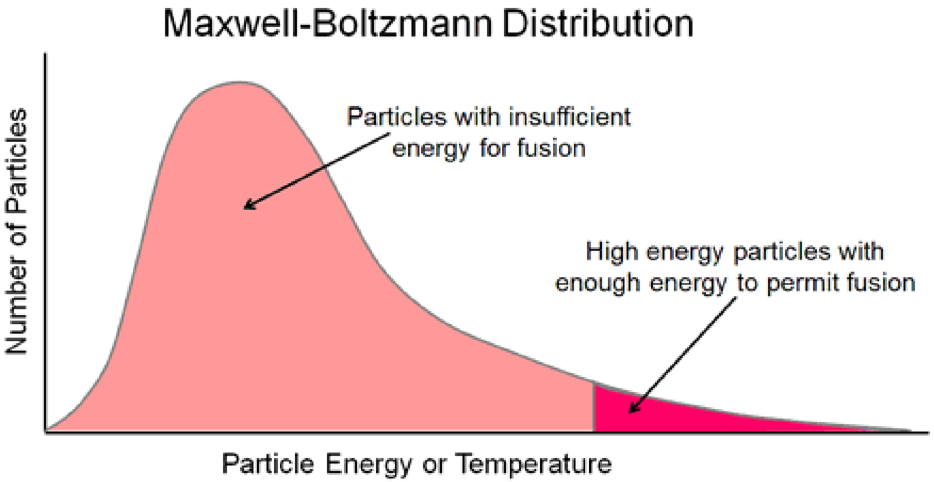
- Increasing fusion reaction probability without losing energy is a better way to approach fusion: take a mixture of deuterium and tritium gas and heat it to the required temperature. → Thermonuclear fusion, this is to be clearly distinguished from the case where individual nuclei are accelerated and collided with each other or with a stationary target.



When a gas is heated, it becomes a plasma

- Collisions in the hot gas quickly knock the electrons off the atoms and produce a mixture of nuclei and electrons. The gas is said to be ionized, and it has a special name—it is called a plasma.





How about the walls?
→ Need for particle confinement
→ Magnetic or inertial

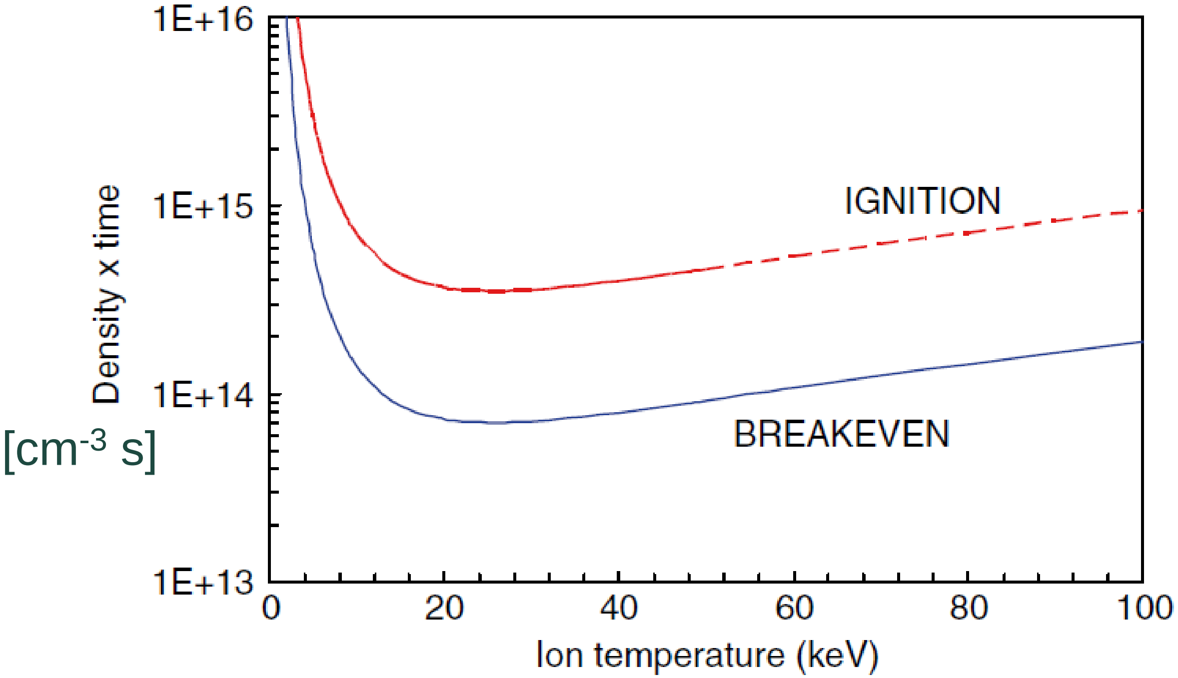
Lawson criterion

- One fundamental question is to determine the conditions required for a net energy output from fusion. Energy is needed to heat the fuel up to the temperature required for fusion reactions, and the hot plasma loses energy in various ways.
- John Lawson, a physicist at the UK Atomic Energy Research Establishment at Harwell, showed in the mid-1950s that "it is necessary to maintain the plasma density (n) multiplied by the confinement time (τ_E) greater than a specified value."

Breakeven and ignition

- BREAKEVEN stands for scientific breakeven ($Q = 1$), in which the fusion energy just balances the energy needed to create the plasma.
- IGNITION, is the $n\tau_E$ required for a self-sustaining plasma, in which the plasma heats itself without additional energy ($Q \rightarrow \infty$). That happens because one of the products of a DT reaction is a charged a-particle, which is trapped by the magnetic field and stays in the plasma keeping the D's and T's hot with its share of the fusion energy.

$$Q = \frac{P_{fusion}}{P_{external}}$$

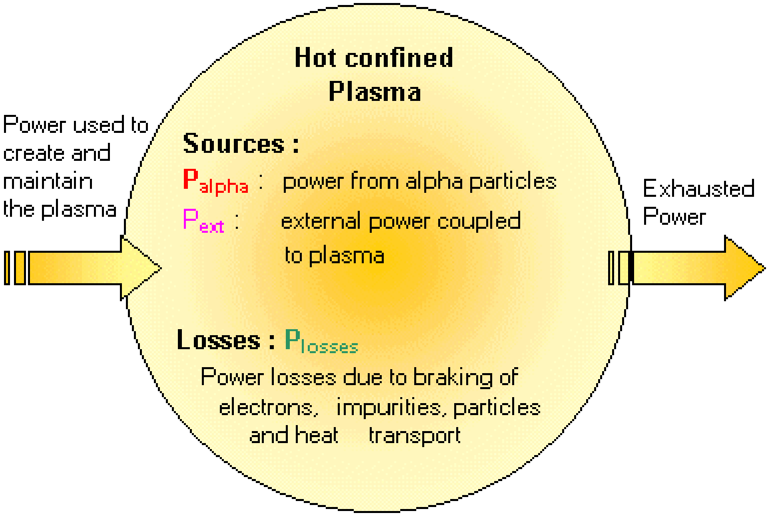


Ignition condition

- The condition for ignition in magnetic confinement is calculated by setting the alpha particle heating equal to the rate at which energy is lost from the plasma.

$$\cancel{P_{ext}} + P_\alpha = P_{loss}$$

For ignition, $P_{ext} = 0$



Power used to create and maintain the plasma

Hot confined Plasma

Sources :

$\mathbf{P}_{\mathrm{alpha}}$: power from alpha particles

P_{ext} : external power coupled to plasma

Losses : P_{losses}

Power losses due to braking of electrons, impurities, particles and heat transport

Exhausted Power

$$k = 1.6 \times 10^{-16}\ \mathrm{J/keV}$$

$$P_\alpha = n_D n_T < \sigma v > \times\ (3.5 \times 10^3\ \mathrm{keV}) \times k = \frac{1}{4} n^2 < \sigma v > \times\ (3.5 \times 10^3) \times k \quad [\mathrm{W/m^3}]$$

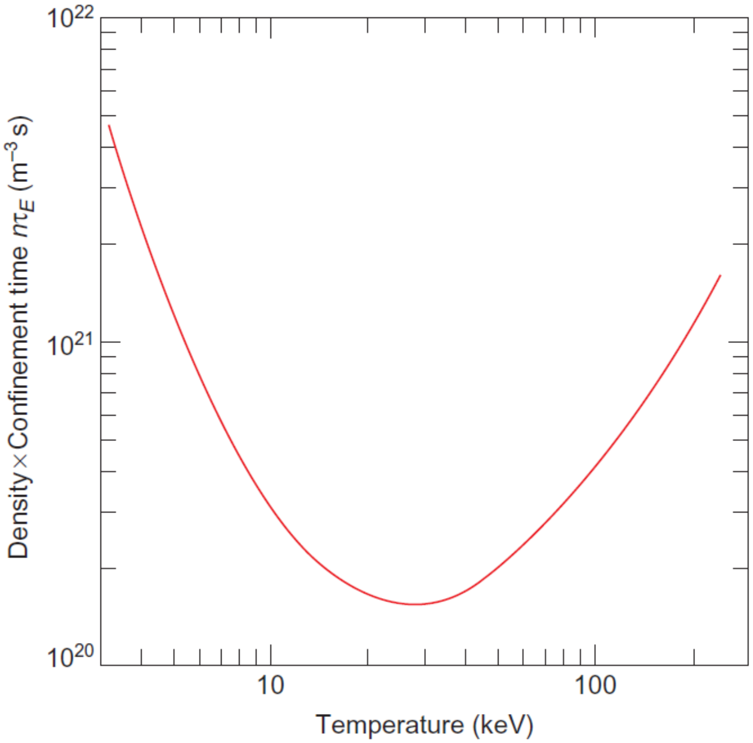
$$P_{loss} = \frac{E_i + E_e}{\tau_E} = \frac{3nkT}{\tau_E} \quad [\mathrm{W/m^3}]$$

$$5 \times 10^{22}\ @T = 30\ \mathrm{keV}$$

$$\boxed{n\tau_E = \frac{12}{3.5 \times 10^3} \cdot \frac{T\ (\mathrm{keV})}{< \sigma v > (\mathrm{m^3 s^{-1}})} \approx 1.7 \times 10^{20} \quad [\mathrm{m^{-3} s}]}$$

Ignition condition for D-T reaction

- Usually τ_E is also a function of temperature ($\tau_E \sim T^{-1.25}$), and the optimum temperature for DT ignition in a tokamak down to around 10 keV.



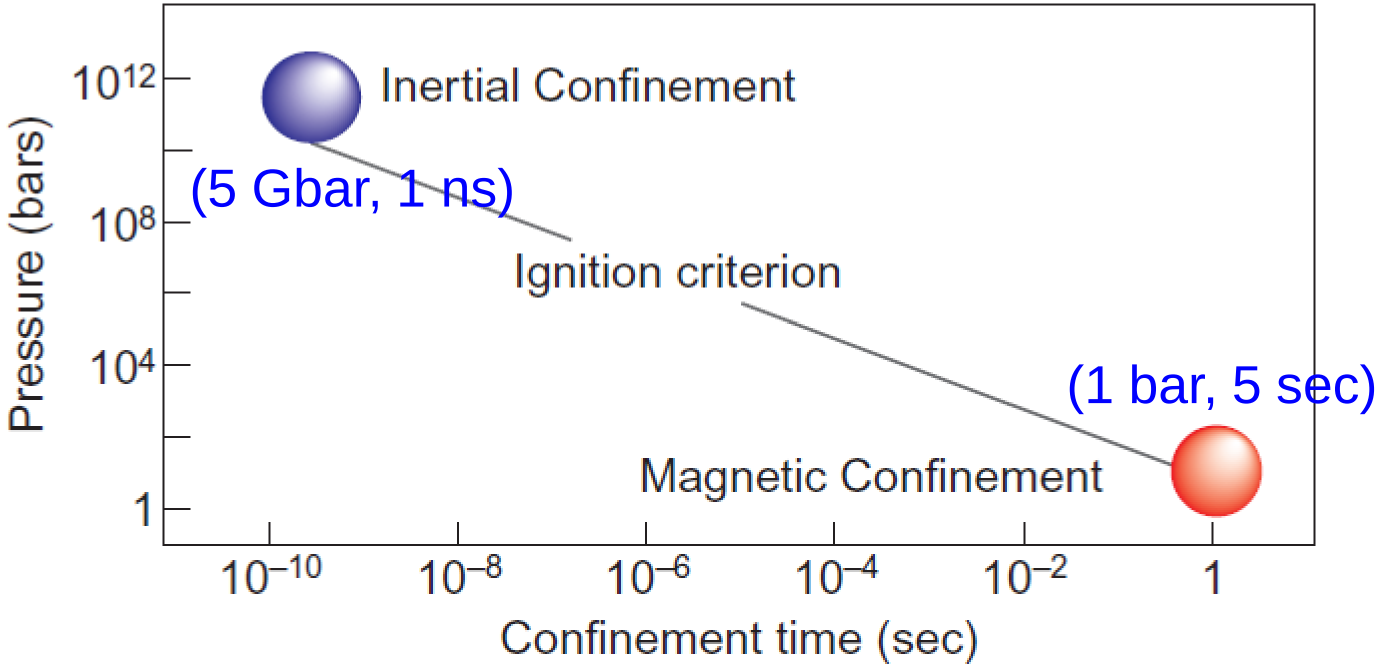
- In the temperature range 10–20 keV, the DT reaction rate $<\sigma v>$ is proportional to T^2. In addition, by considering other issues, we obtain the triple product:

$$\boxed{nT\tau_E \approx 6 \times 10^{21} \quad [\mathrm{m^{-3}\ keV\ s}]}$$

Ignition condition for D-T reaction

- The product of density and temperature is the pressure of the plasma. The ignition condition then becomes:

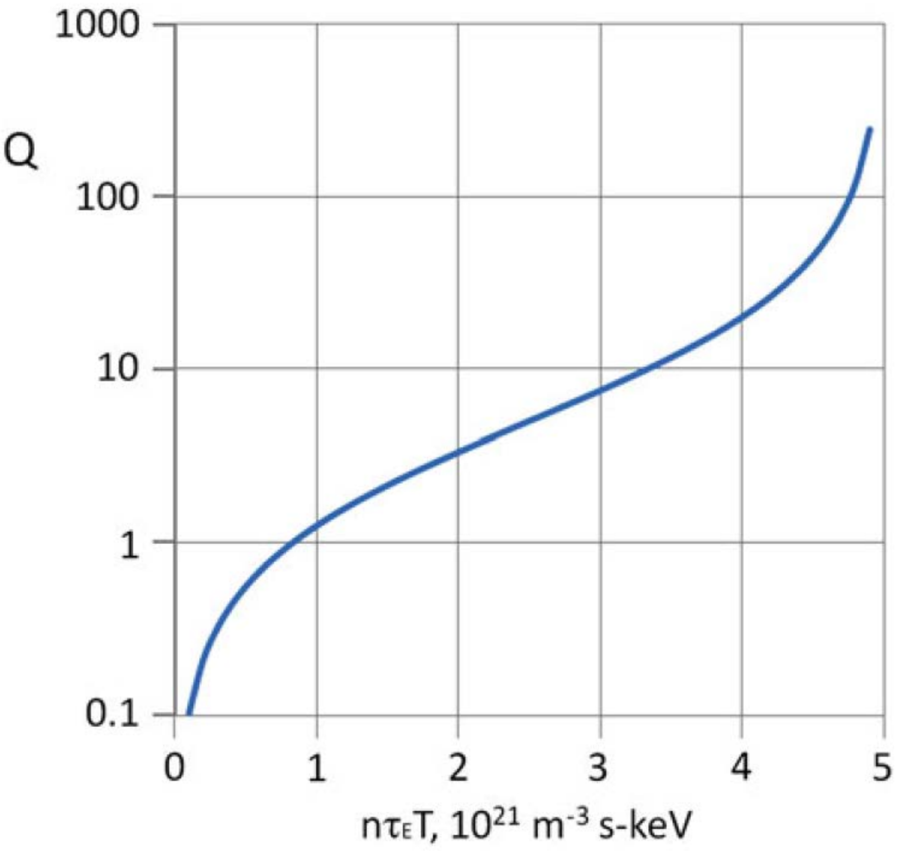
$\boxed{nT\tau_E \approx 6 \times 10^{21} \quad [\mathrm{m^{-3}\ keV\ s}]}$ ⇨ $\boxed{p\tau_E \approx 5 \quad [\mathrm{bar\ s}]}$



(5 Gbar, 1 ns)

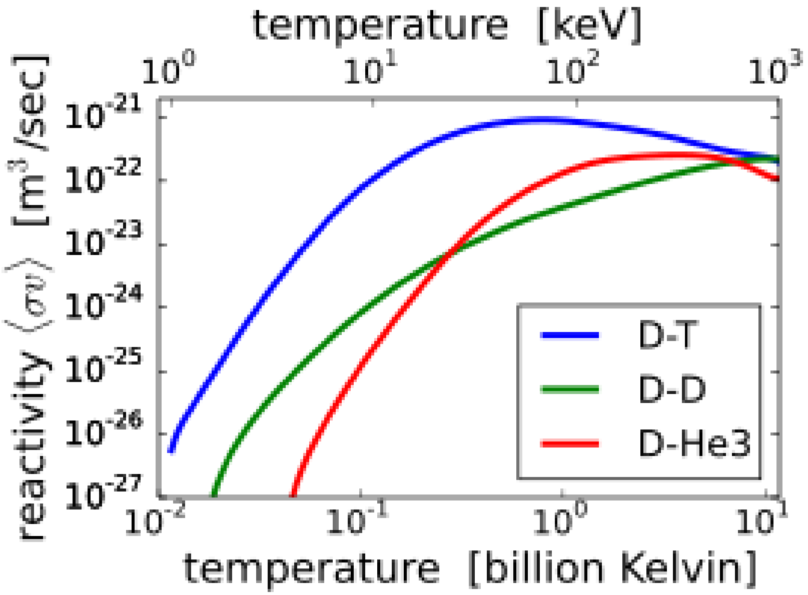
(1 bar, 5 sec)

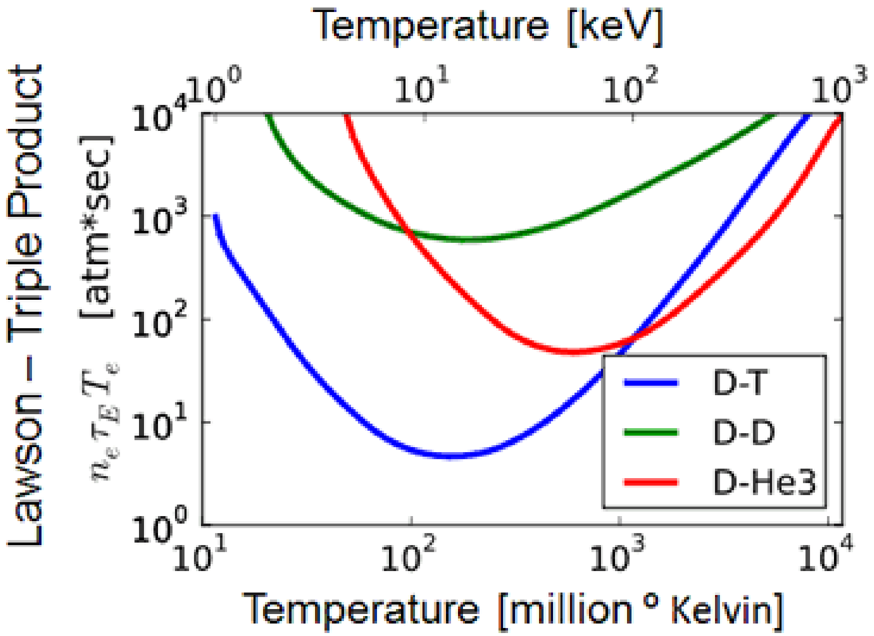
Q versus triple product for D-T reaction



- A fusion reactor ($Q > 10$) requires values of the "triple product" $nT\tau_E > 3 \times 10^{21} \quad [\mathrm{m}^{-3}\ \mathrm{keV\ s}]$.

Triple products for various fusion reactions





Fusion power density

- For a monoenergetic ion beam striking a target ion, the reaction rate is proportional to the effective "cross section" area σ of the target. The reaction rate between monogenetic ions with speed v and density n_1 striking target ions of density n_2 is given by

$$\text{Reaction rate: } R = n_1 n_2 \sigma v \quad [\text{reactions/m}^3\text{s}]$$

- For thermonuclear fusion, the ions are not monoenergetic, but are assumed to have Maxwellian velocity distributions characterized by a temperature T. Then the σv must be averaged over the velocity distribution function.
- The fusion power density of a DT plasma (assuming $n_D = n_T = n/2$) is given by

$$P_{DT} = n_D n_T < \sigma v > \times\, W_{DT} = \frac{1}{4} n^2 < \sigma v > \times\, (2.82 \times 10^{-12} \text{ J/fusion}) \quad [\text{W/m}^3]$$

- Q: Estimate the fusion power density and pressure in a DT plasma with $n = 10^{20} \text{ m}^{-3}$ and $T = 20 \text{ keV}$.

$$P_{DT} = \frac{1}{4} \times (10^{20})^2 \times (4 \times 10^{-22}) \times (2.82 \times 10^{-12}) = 2.82 \times 10^{6} \quad [\text{W/m}^3]$$