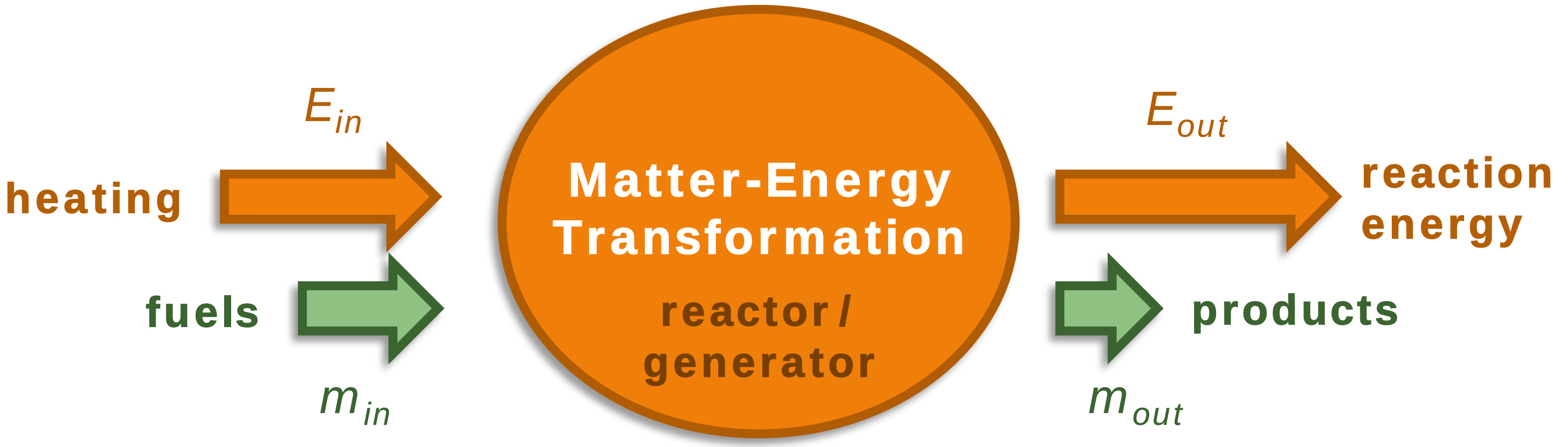
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

What is nuclear fusion?

Matter and Energy

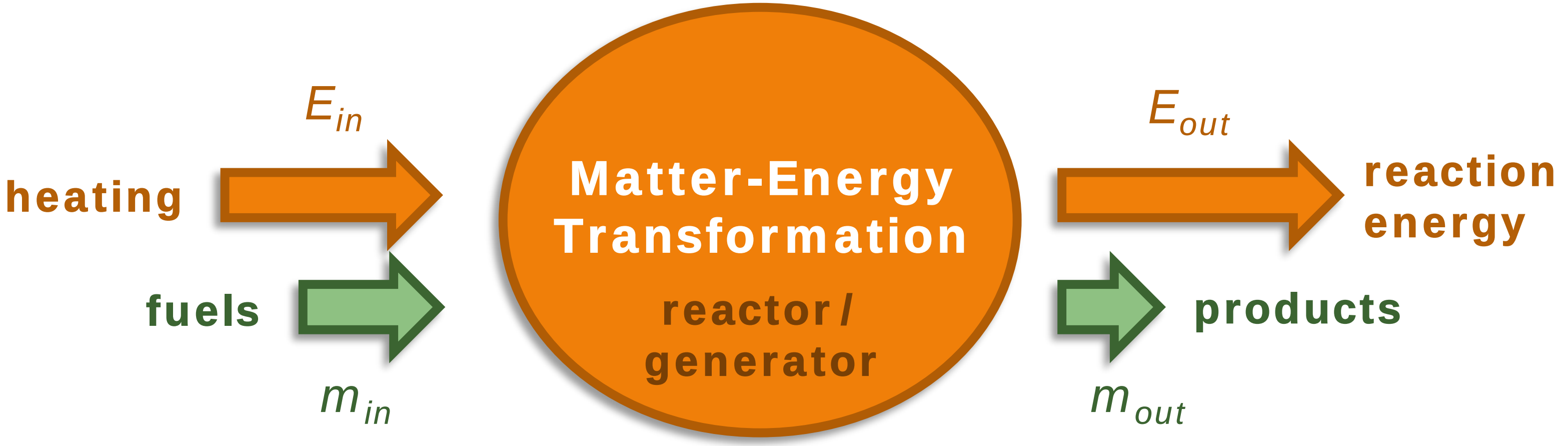


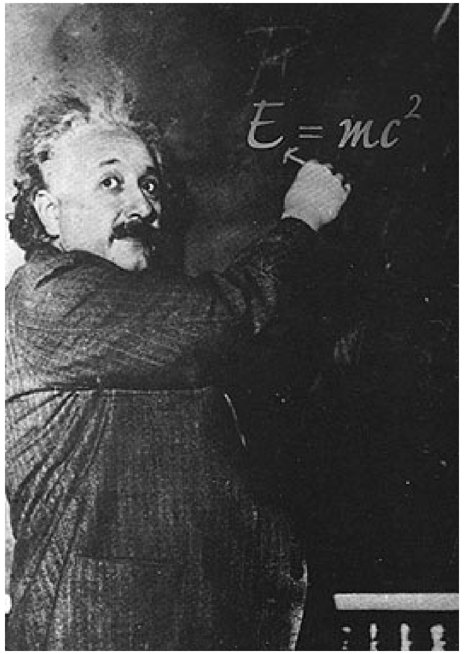
- **Chemical reactions (combustion)**

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 3\,eV$$

$$1\,eV = \frac{1.6\times10^{-19}\,J}{1.38\times10^{-28}\,J/K} = 11600K$$

Matter and Energy





http://www.meteoweb.eu/2011/09/e-possibile-superare-la-velocita-della-luce-teoria-della-relativita-a-rischio/88437/, Dec, 2014

- Chemical reactions (combustion)
- Fission process
- Fusion process

- Total energy conservation including rest mass energy

$$E_{in} + M_{in} \rightarrow E_{out} + M_{out}$$

- If $\Delta m = M_{out} - M_{in} < 0$, then we can get $E_{out} > E_{in}$.

Mass Defect Energy of Nuclear Reaction

reactants **products**

$$a + b \rightarrow d + e$$

$$E^*_{before} = E^*_{after}$$ **Total energy**

$$(E_{k,a} + m_a c^2) + (E_{k,b} + m_b c^2) = (E_{k,d} + m_d c^2) + (E_{k,e} + m_e c^2)$$

For $E_{k,a} + E_{k,b} << Q_{ab}$

$$Q_{ab} = [(m_a + m_b) - (m_d + m_e)]c^2$$
$$= (-\Delta m_{ab})c^2$$

$$\Delta m_{ab} = (m_d + m_e) - (m_a + m_b)$$

$$(m_a c^2 + m_b c^2) \approx (m_d c^2 + m_e c^2) + E_{k,d} + E_{k,e}$$

$$Q_{ab} \approx E_{k,d} + E_{k,e} = \frac{1}{2} m_d v_d^2 + \frac{1}{2} m_e v_e^2$$

Mass Defect Energy of Nuclear Reaction

$$Q_{ab} \approx E_{k,d} + E_{k,e} = \frac{1}{2}m_d v_d^2 + \frac{1}{2}m_e v_e^2$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 3\,eV$$

Momentum conservation for reactions with CM at rest

$$m_d v_d = m_e v_e$$

Derive!

$$\frac{1}{2}m_d v_d^2 = \frac{m_e}{m_d + m_e}\left(\frac{m_d + m_e}{m_e}\frac{1}{2}m_d v_d^2\right)$$

$$= \frac{m_e}{m_d + m_e}\left(\frac{1}{2}\frac{m_d^2}{m_e}v_d^2 + \frac{1}{2}m_d v_d^2\right)$$

$$= \frac{m_e}{m_d + m_e}\left(\frac{1}{2}\frac{m_d^2}{m_e}\frac{m_e^2}{m_d^2}v_e^2 + \frac{1}{2}m_d v_d^2\right)$$

$$E_{k,d} \approx \left(\frac{m_e}{m_d + m_e}\right)Q_{ab}, \quad E_{k,e} \approx \left(\frac{m_d}{m_d + m_e}\right)Q_{ab}$$

Ex) d-t fusion reaction $d + t \rightarrow n + \alpha$

$$Q_{dt} = 17.6\ \mathrm{MeV}$$

$$E_{k,n} \approx \frac{4}{5}Q_{dt} \approx 14.1\ \mathrm{MeV}, \quad E_{k,\alpha} \approx \frac{1}{5}Q_{dt} \approx 3.5\ \mathrm{MeV}$$

$$m_n \approx m_p$$

$$m_p = 1.672621 \times 10^{-27}\,kg$$

$$m_n = 1.674927 \times 10^{-27}\,kg$$

Fusion in Nature

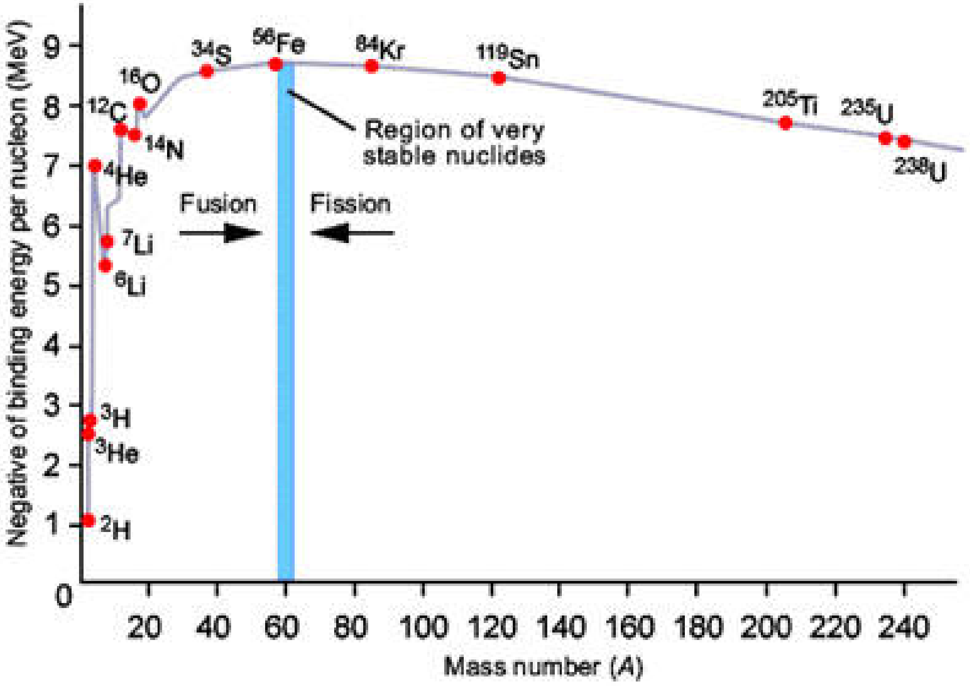
- **Nuclei** are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.

- **Binding energy**: the amount of energy released when a particular nucleus is formed.

$$Zp + (A - Z)n \rightarrow {}^{A}_{Z}X + B.E.$$

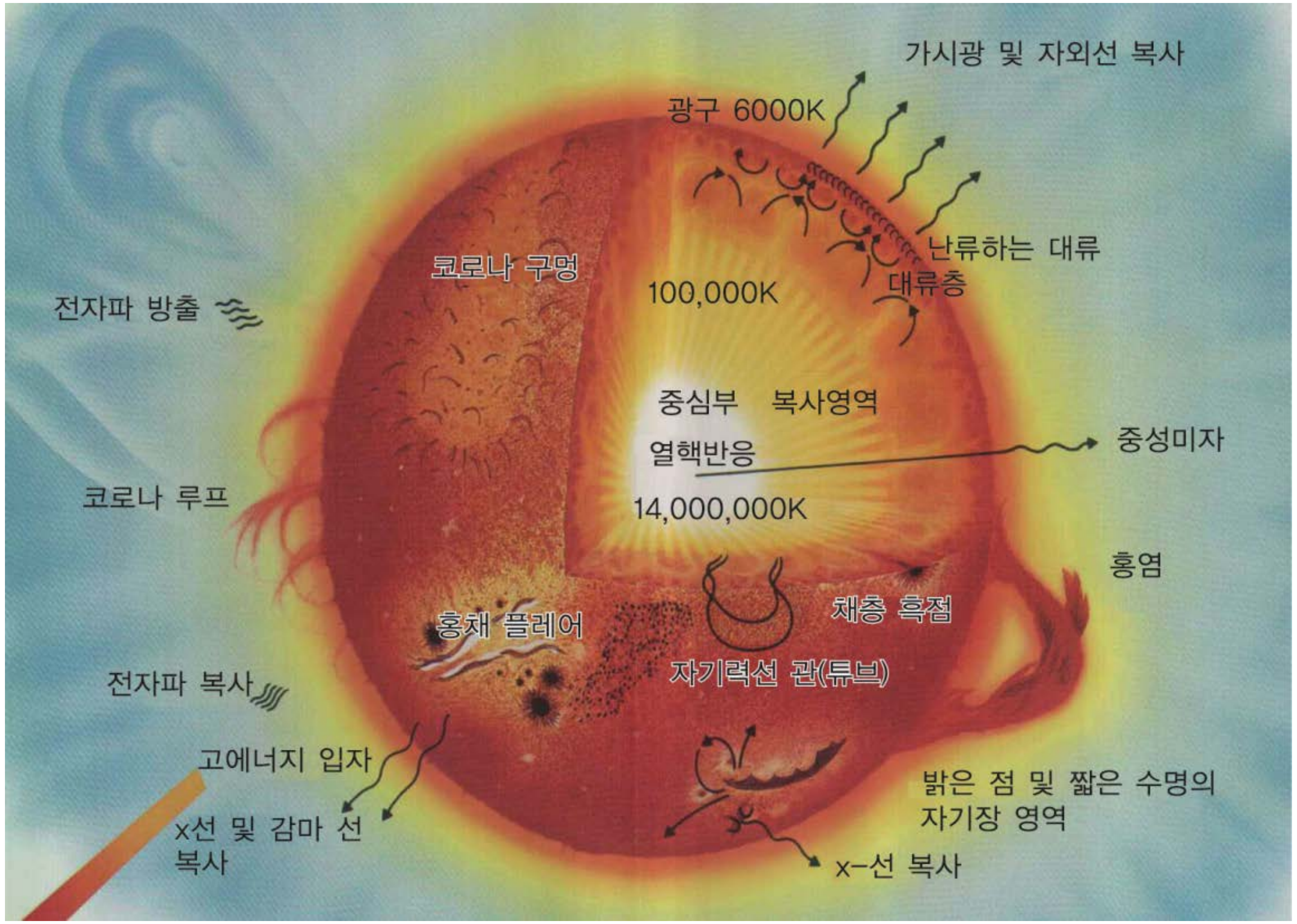
$$B.E. \equiv -[(m_X - Zm_p + (A - Z)m_n)]c^2 = -\Delta mc^2$$

Δm < 0: released energy (exothermic or exoergic)



http://www.daviddarling.info/encyclopedia/B/binding_energy.html

Fusion in Nature



Sun producing 3.8×10^{26} J/s equivalent to 4.3×10^{9} kg

Sun composed of proton (73%), He (25%), etc

How old is the sun?

How long is the sun's lifetime?

Fusion in Nature

- **Fusion reactions by which stars convert hydrogen to helium**

- The PP (proton-proton) chain: in stars the mass of the Sun and less

- The CNO cycle (Bethe-Weizsäcker-cycle): in more massive stars

Nobel prize in physics 1967
“for his contribution to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars”

Hans Albrecht Bethe
(1906. 7. 2 – 2005. 3. 6)

http://www.nobelprize.org/nobel_prizes/physics/laureates/1967/bethe-bio.html

Fusion in Nature

- **Fusion reactions by which stars convert hydrogen to helium**

- The PP (proton-proton) chain: in stars the mass of the Sun and less

- The CNO cycle (Bethe-Weizsäcker-cycle): in more massive stars

One of the most impressive discoveries was the origin of the stars, that makes them continue to burn. One of the men who discovered this was out with his girl friend the night after he realized that nuclear reactions must be going on in the stars in order to make them shine. She said "Look at how pretty the stars shine!" He said "Yes, and right now I am the only man in the world who knows why they shine." She merely laughed at him. She was not impressed with being out with the only man who, at that moment, knew why stars shine. Well, it is sad to be alone, but that is the way it is in this world.

- The Feynman Lectures on Physics I, p.3-7

Fusion in Nature

- **The PP (Proton-Proton) Chain**

Step 1: Smash two protons together to make deuterium

$$p + p \rightarrow d + \beta^{+} + \nu + 1.2\,MeV \qquad\qquad p \rightarrow n + \beta^{+} + \nu - 0.782 MeV$$

Positron: antiparticle of the electron-like an electron with charge of +1e
Neutrino: electrically neutral, weakly interacting elementary subatomic particle

http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/ppchain.html

Fusion in Nature

- **The PP (Proton-Proton) Chain**

Step 2: A proton crashes into a deuterium nucleus, making ^3He

$$p + d \rightarrow {}^3He + \gamma + 5.5\,MeV$$

Gamma ray: electromagnetic radiation of an extremely high frequency (very high energy photon)

Do Steps 1 and 2 again so to have two ^3He nuclei.

http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/ppchain.html

Fusion in Nature

- **The PP (Proton-Proton) Chain**

Step 3: Mash two helium-3 nuclei together to make helium-4

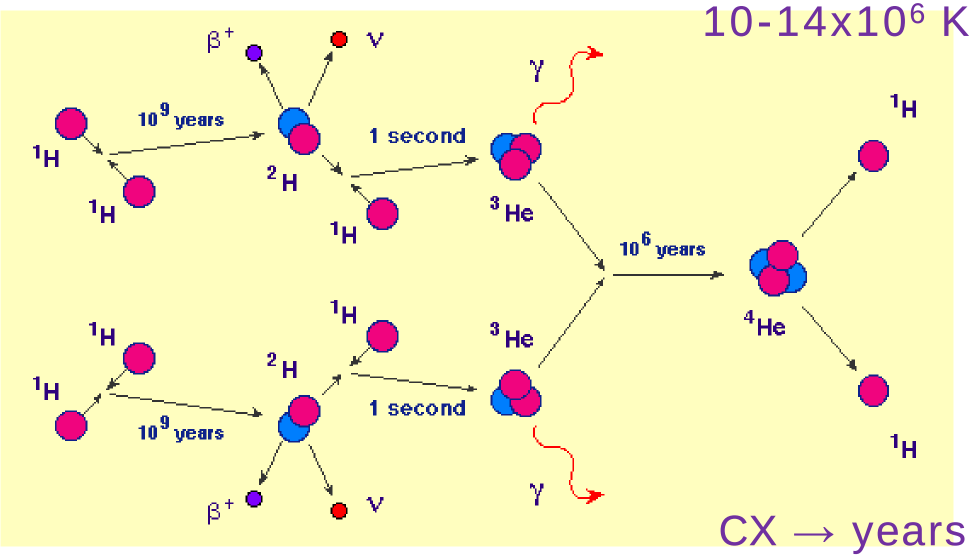
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p + 12.9\ MeV$$

http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/ppchain.html

Fusion in Nature

- **The PP (Proton-Proton) Chain**

10-14x10⁶ K



CX → years

$$p + p \rightarrow d + \beta^{+} + \nu + 1.2\ MeV$$

$$p + d \rightarrow {}^{3}He + \gamma + 5.5\ MeV$$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p + 12.9\ MeV$$

PPII Chain (14-23x10⁶ K)

$$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

$$^{7}Be + \beta^{-} \rightarrow {}^{7}Li + \nu$$

$$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$$

PPIII Chain (> 23x10⁶ K)

$$^{7}Be + p \rightarrow {}^{8}B + \gamma$$

$$^{8}B \rightarrow {}^{8}Be + \beta^{+} + \nu$$

$$^{8}Be \rightarrow {}^{4}He + {}^{4}He$$

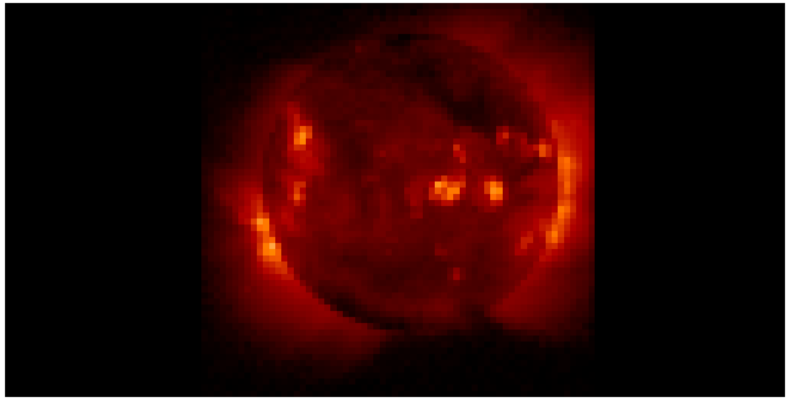
nucleosynthesis

http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html

Fusion in Nature

- The PP (Proton-Proton) Chain

Why are other processes needed to explain stars?



$$T_{Sun} \leq 15 \times 10^6 K$$

- Most of ^{4}He nuclei being produced in the Sun are born in the PP chain (98.3 %).

http://www.nasa.gov/mission_pages/galex/20070815/f.html

Fusion in Nature

- **The CNO Cycle**

$$^{12}C + p \rightarrow {}^{13}N + 1.9\ MeV$$

$$^{13}N \rightarrow {}^{13}C + \beta^{+} + \nu + 1.5\ MeV$$

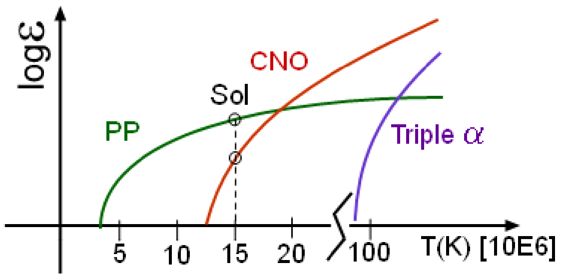
$$^{13}C + p \rightarrow {}^{14}N + 7.6\ MeV$$

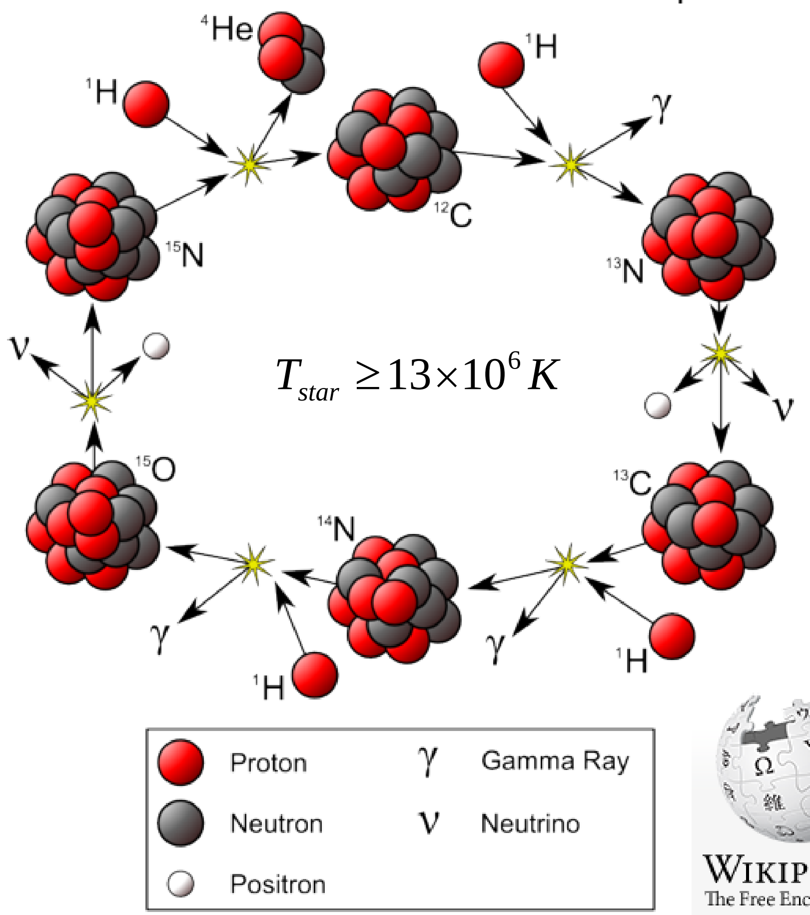
$$^{14}N + p \rightarrow {}^{15}O + 7.3\ MeV$$

$$^{15}O \rightarrow {}^{15}N + \beta^{+} + \nu + 1.8\ MeV$$

$$^{15}N + p \rightarrow {}^{12}C + \alpha + 5.0\ MeV$$

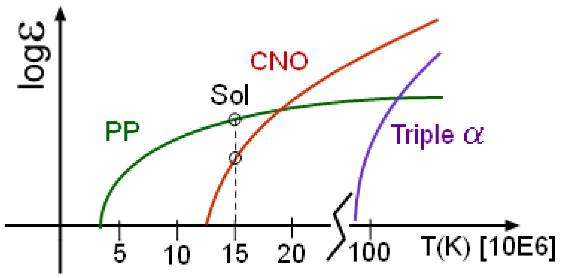
$$4p \rightarrow \alpha + 2\beta^{+} + 2\nu + 25.1\ MeV$$





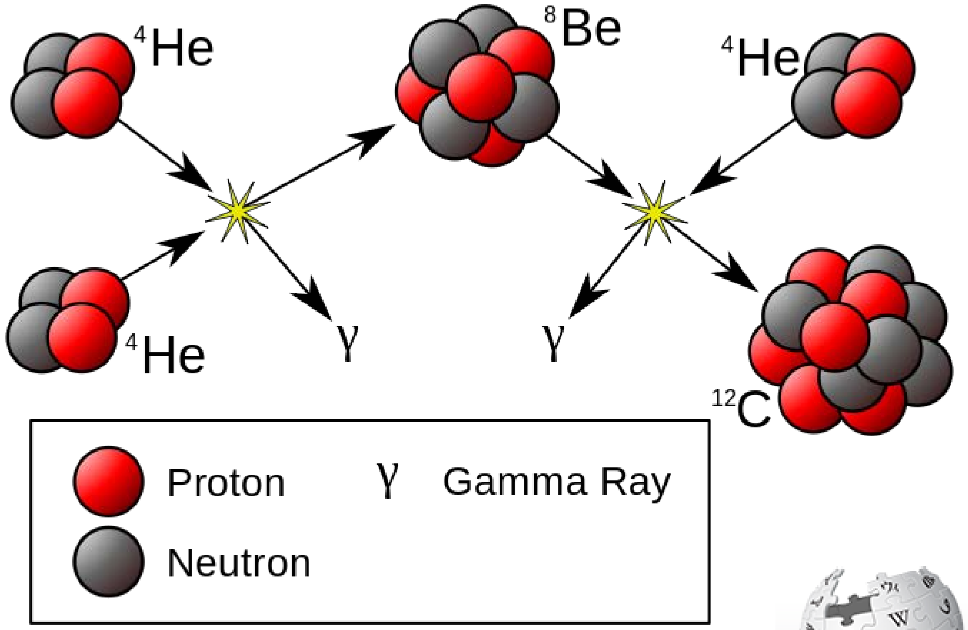
Fusion in Nature

- **The triple alpha process**



$$\alpha + \alpha \rightarrow {}^{8}Be - 92\ keV$$

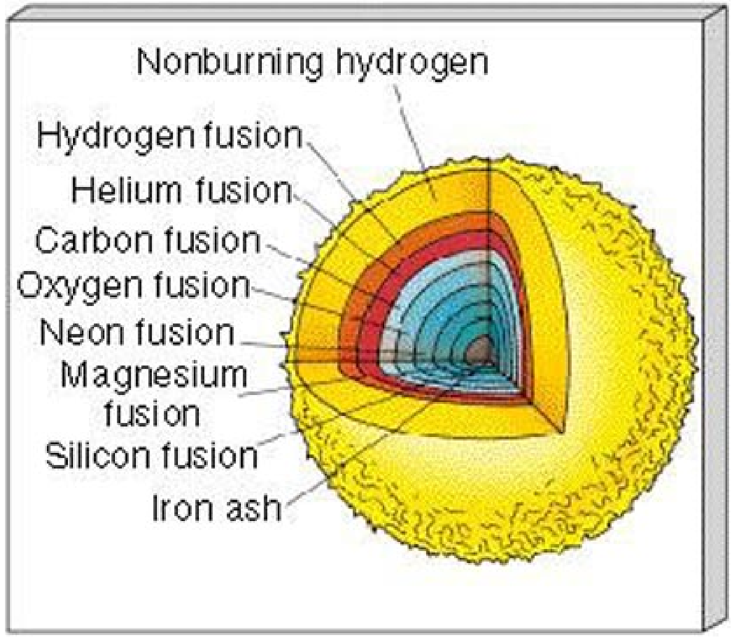
$$^{8}Be + \alpha \rightarrow {}^{12}C + \gamma + 7.367\ MeV$$

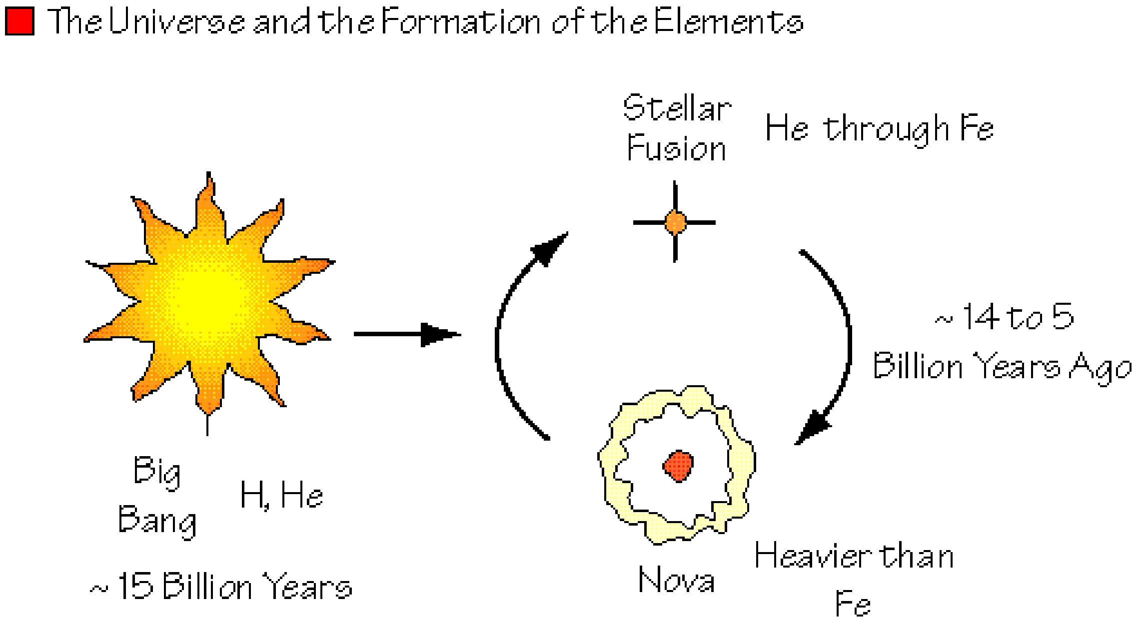


WIKIPEDIA The Free Encyclopedia

Fusion in Nature

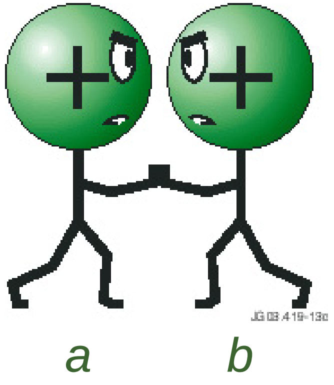
Layers of Fusion in the final stage of a massive star





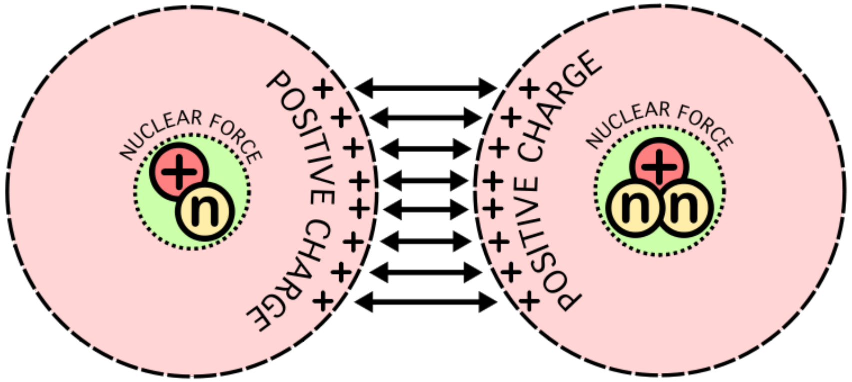
http://jcconwell.wordpress.com/2009/07/20/formation-of-the-elements/
http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/earth_origin_lecture.html

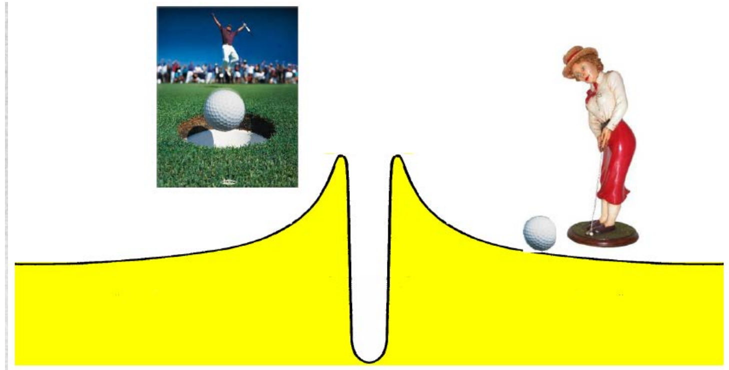
Physical Characterization of Fusion Reaction



$$F_{g,a} = -G \frac{m_a m_b}{r^3} \vec{r}$$

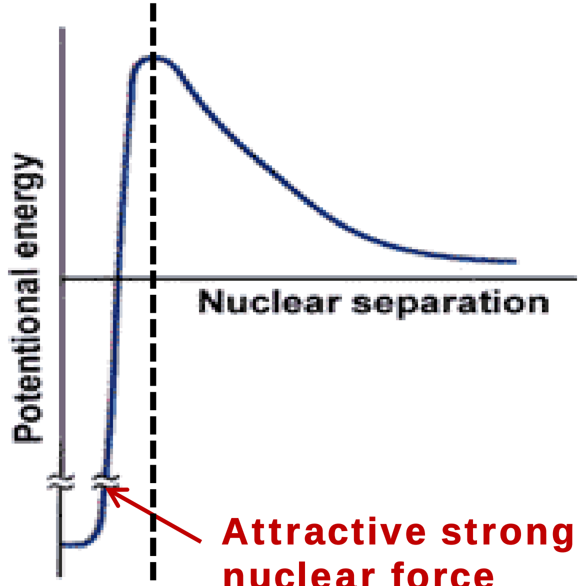
$$F_{c,a} = \frac{1}{4\pi\varepsilon_0} \frac{q_a q_b}{r^3} \vec{r}$$





- The electrostatic force caused by positively charged nuclei is very strong over long distances, but at short distances the nuclear force is stronger.
- As such, the main technical difficulty for fusion is getting the nuclei close enough to fuse.

Physical Characterization of Fusion Reaction



$$U(R_0) = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{R_0} \sim 0.4\,\text{MeV for } d, t, p$$

Sun: $1.4\text{x}10^6$ eV

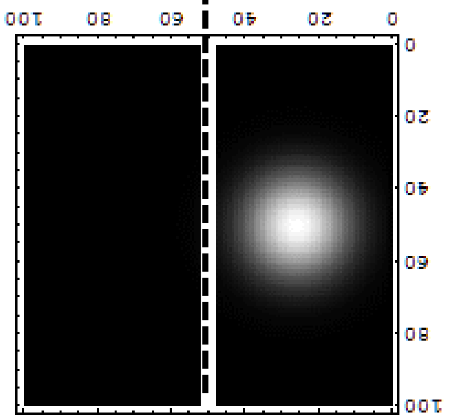
$$R_0 \approx R_p\left(A_a^{1/3} + A_b^{1/3}\right), \quad R_p = (1.3 - 1.7)\times 10^{-15}\, m$$

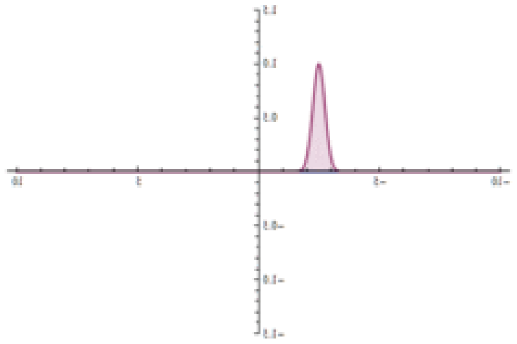
$$\Pr(tunneling) \propto \frac{1}{v_r}\exp[-\gamma\frac{q_a q_b}{v_r}]$$

$$E << V_0$$

$$|T|^2 = \frac{(2k_0/\kappa)^2}{(2k_0/\kappa)^2 + \left(\kappa^2 + k_0{}^2\right)^2 \sinh^2 \kappa a}$$

$$\cong \left(\frac{4k_0\kappa}{\kappa^2 + k_0{}^2}\right)^2 e^{-2\kappa a}$$



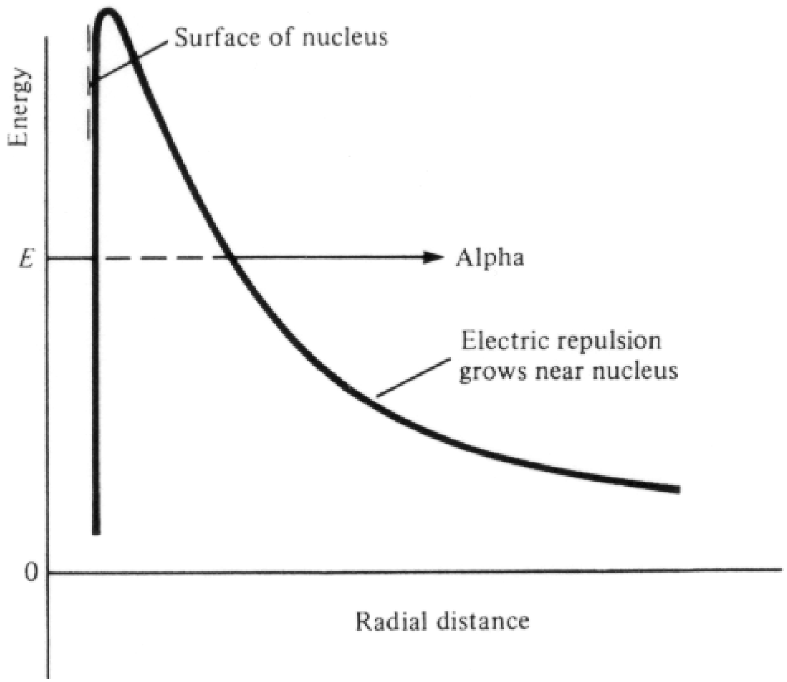


Reflection and tunneling of an electron wave packet directed at a potential barrier

A. B. Balantekin and N. Takigawa, 'Quantum tunneling in nuclear fusion', Rev. Mod. Phys. 70, 77 (1998).

Physical Characterization of Fusion Reaction

Potential barrier around a uranium nucleus presented to an alpha particle. The central well is due to the average nuclear attraction of all the nucleons and the hill is due to the electric repulsion of the protons. Alpha particles with energy *E* trapped inside the nuclear well may still escape to become alpha rays, by quantum mechanically tunnelling through the barrier.



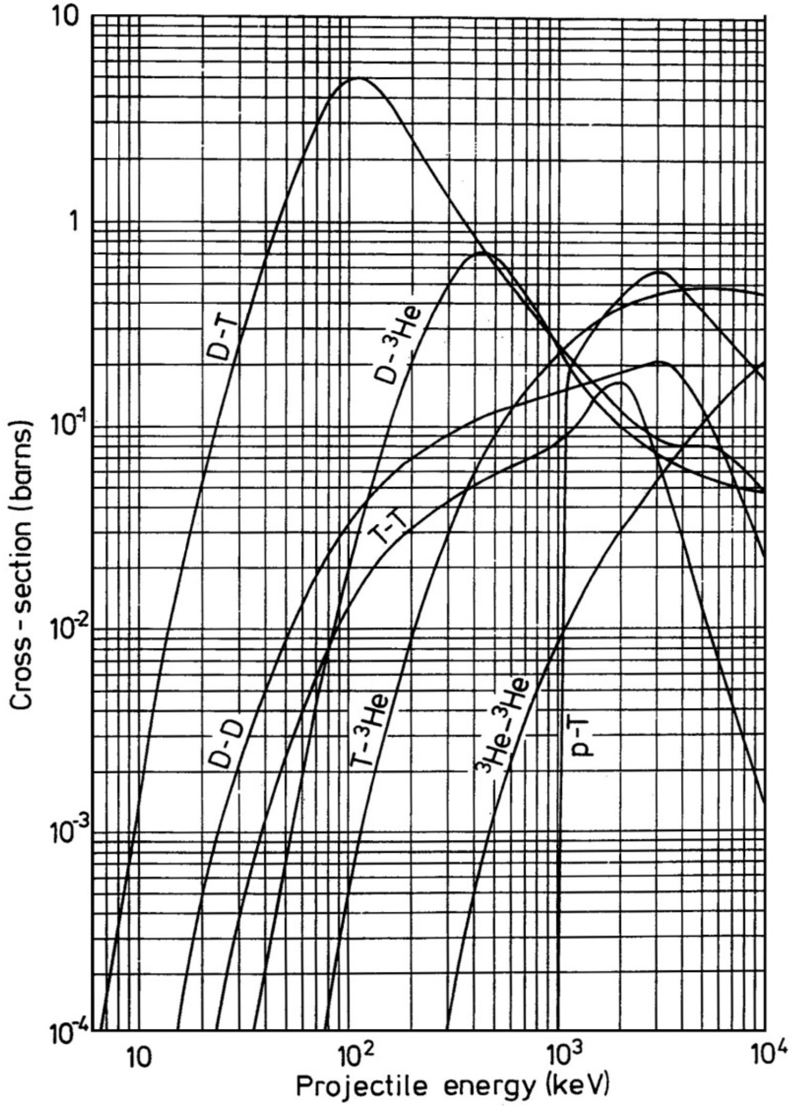
George Gamow
(1904-1968)

Max Born
(1882-1970)

- By 1928, George Gamow had solved the theory of the alpha decay of a nucleus via tunneling. After attending a seminar by Gamow, Max Born recognized the generality of quantum-mechanical tunneling.

(Max Born, Nobel Prize in Physics 1954)

Fusion Reaction Cross Sections



- Fusion cross section for low energy $E_{CM} < U(R_0)$ by quantum mechanical tunneling process:

$$\sigma_{ab}(E) = \frac{A}{E} e^{-B/\sqrt{E}}$$

Gamow theory (1938)

$$A = const., \quad B = 2^{-1/2} \pi m_r^{1/2} Z_a Z_b e^2 / h\varepsilon_0$$

$$1 barn = 10^{-24} cm^2 = 10^{-28} m^2$$

Fusion Reaction Rate Parameter (Reactivity)

- **Fusion reaction rate density**

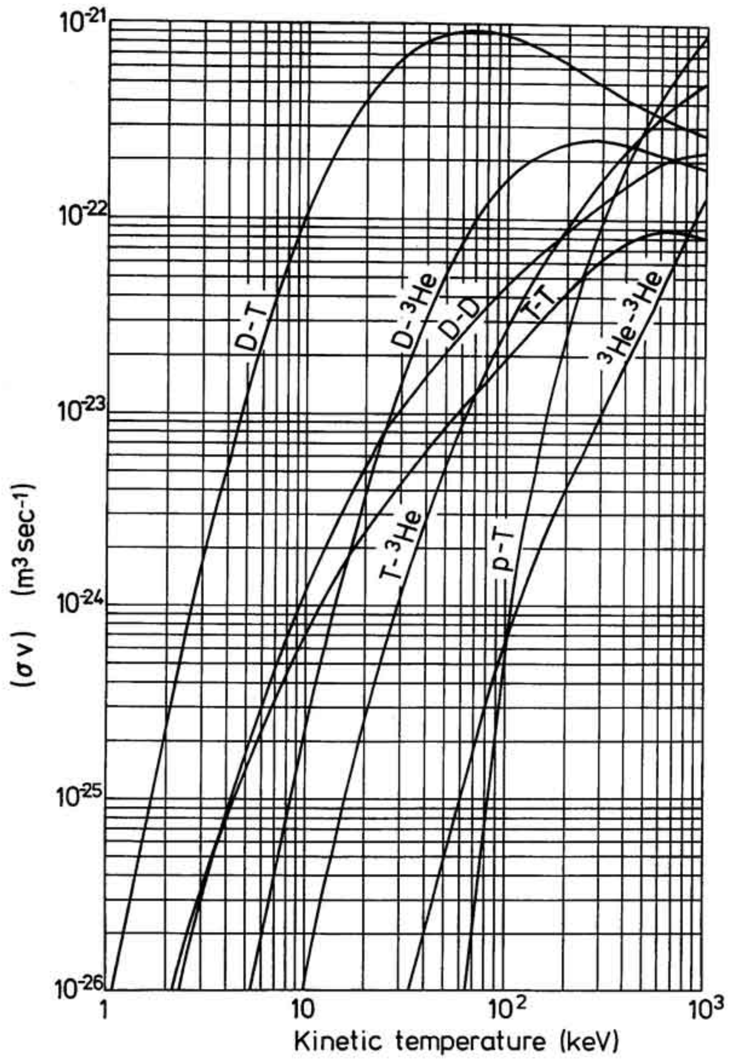
$$R_{fu} \propto N_a N_b v_r \qquad v_r = \left|\vec{v}_a - \vec{v}_b\right|$$

$$R_{fu} = N_a N_b < \sigma v_r >_{ab}$$

- **σ-*v* parameter**

$$< \sigma v >_{ab} = \int_{\vec{v}_a}\int_{\vec{v}_b} \sigma_{ab}\left(\left|\vec{v}_a - \vec{v}_b\right|\right)\left|\vec{v}_a - \vec{v}_b\right| F_a(\vec{v}_a) F_b(\vec{v}_b) d^3 v_a d^3 v_b$$

Fusion Reaction Rate Parameter (Reactivity)



- Thermodynamic equilibrium $F_x(v_x) \rightarrow M_x(v_x)$
- Both species at the same temperatures

http://www.scienceall.com/jspJavaPopUp.do?classid=CS000140&articleid=611&bbsid=146&popissue=java

Fusion Reaction Rate Parameter (Reactivity)

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$$R_{fu} \propto N_a N_b v_r \qquad v_r = \left|\vec{v}_a - \vec{v}_b\right|$$

$$R_{fu} = N_a N_b < \sigma v_r >_{ab}$$

- **σ-*v* parameter**

$$< \sigma v >_{ab} = \int_{\vec{v}_a}\int_{\vec{v}_b} \sigma_{ab}\left(\left|\vec{v}_a - \vec{v}_b\right|\right)\left|\vec{v}_a - \vec{v}_b\right| F_a(\vec{v}_a) F_b(\vec{v}_b) d^3 v_a d^3 v_b$$

- **Fusion power density**

$$P_{fu} = R_{fu} Q_{fu} = N_a N_b < \sigma v >_{ab} Q_{fu}$$

Which fusion fuels to utilize for our fusion reactor?

Fusion Fuels

- **Possible fusion reactions**

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

$$d + d \rightarrow p + t + 4.1\,\text{MeV}$$

$$\rightarrow n + {}^{3}He + 3.2\,\text{MeV}$$

$$d + {}^{3}He \rightarrow p + \alpha + 18.3\,\text{MeV}$$

$$p + {}^{6}Li \rightarrow {}^{3}He + \alpha + 4.0\,\text{MeV}$$

$$p + {}^{9}Be \rightarrow \alpha + {}^{6}Li + 2.1\,\text{MeV}$$

$$\rightarrow d + 2\alpha + 0.6\,\text{MeV}$$

$$p + {}^{11}B \rightarrow 3\alpha + 8.7\,\text{MeV}$$

$$d + {}^{6}Li \rightarrow {}^{7}Be + n + 3.4\,\text{MeV}$$

$$\rightarrow {}^{7}Li + p + 5.0\,\text{MeV}$$

$$\rightarrow p + \alpha + t + 2.6\,\text{MeV}$$

$$\rightarrow 2\alpha + 22.3\,\text{MeV}$$

$$\rightarrow {}^{3}He + \alpha + n + 1.8\,\text{MeV}$$

$$t + t \rightarrow 2n + \alpha + 11.3\,\text{MeV}$$

$${}^{3}He + {}^{3}He \rightarrow 2p + \alpha + 12.9\,\text{MeV}$$

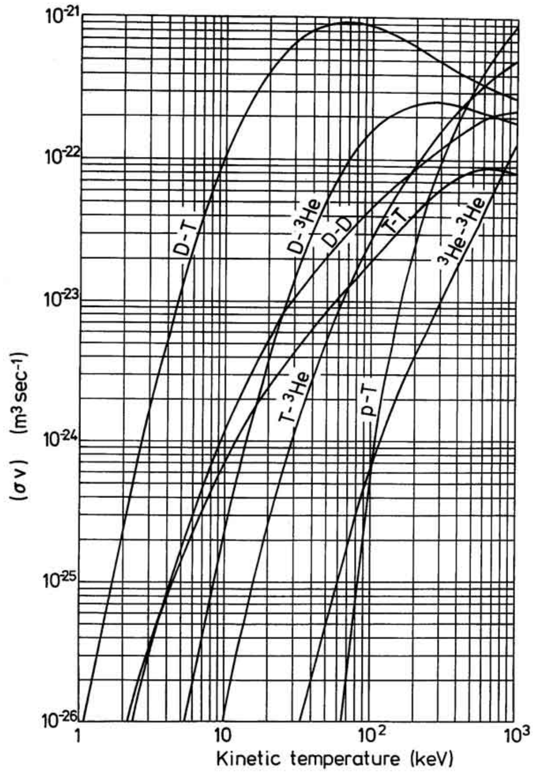
$$t + {}^{3}He \rightarrow n + p + \alpha + 12.1\,\text{MeV}$$

Fusion Fuels

- **Choice of a fusion reaction as a fuel in a fusion reactor**

  - Availability of fusion fuels

  - Requirements for attaining a sufficient reaction rate density



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Fusion Fuels

- **Choice of a fusion reaction as a fuel in a fusion reactor**

- Availability of fusion fuels
- Requirements for attaining a sufficient reaction rate density

- **D-T reaction: 1^{st} generation**

- Considered for the first generation of fusion reactors
- Ample supply of deuterium: d/(p+d)~1/6700 in the world's oceans,
  fresh water lakes, rivers (10 g out of 50 kg)
- Scarce of tritium: radioactive β^- decay with a half life of 12.3 years.
  total steady state atmospheric and oceanic
  quantity produced by cosmic radiation ~ 50 kg

Difference between HWR and LWR?

D-T Fusion

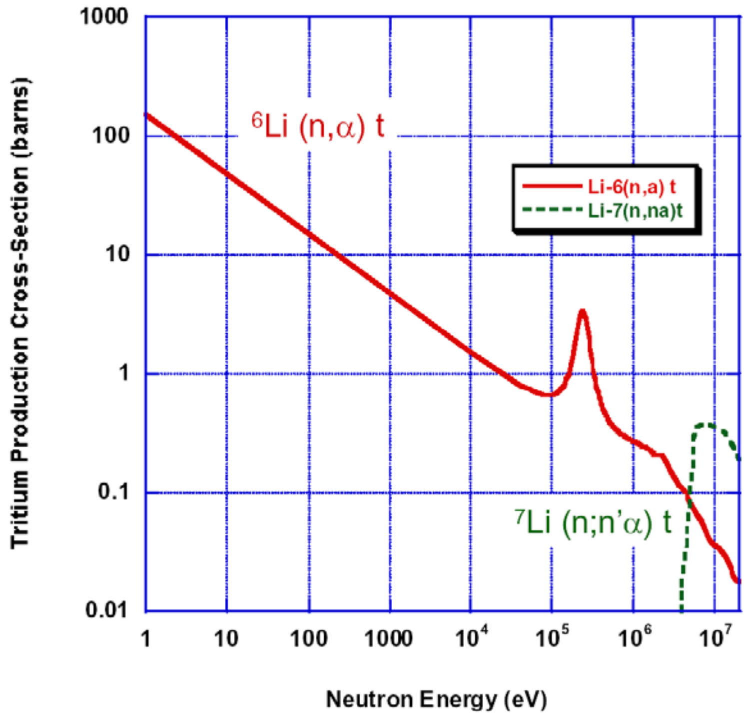
- **D-T reaction: 1st generation**
  - Tritium breeding

$$n + {}^{6}Li \rightarrow t + {}^{4}He + 4.78\,\text{MeV}$$

7.42 % of natural Li

$$n + {}^{7}Li \rightarrow t + {}^{4}He + n' - 2.47\,\text{MeV}$$

92.58 % of natural Li



The $^{7}Li\ (n,n'\alpha)t$ reaction is a threshold reaction and requires an incident neutron energy in excess of 2.8 MeV.

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

D-T Fusion

Silvery-white lithium floating in oil)

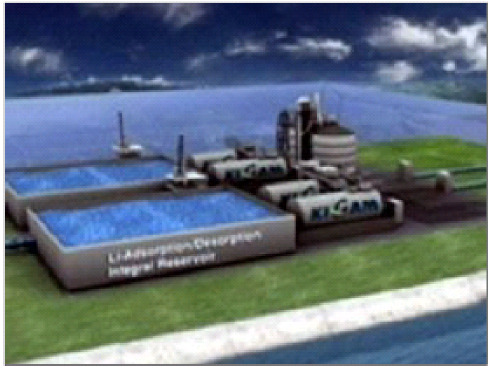
The total lithium content of seawater is very large and is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 parts per million (ppm).

Deuterium: 13-150 ppm

YTN 뉴스 인쇄하기 인쇄하기 창닫기

'리튬' 대량생산 공장 2015년 가동

2010-02-02 12:00



2차 전지와 차세대 핵융합 발전 원료로 사용되는 '리튬'이 상용화 플랜트 공정과 설비시설을 거쳐 오는 2015년부터 대량 생산됩니다.

지난해 5월 바닷물에서 리튬을 추출하는 원천기술을 확보한 국토해양부와 한국지질자원연구원은 포스코와 공동으로 300억 원을 투자해 리튬의 대량 생산을 위한 상용화 플랜트 공정과 설비를 갖추기로 했다고 밝혔습니다.

상용화 사업은 2014년까지 시험플랜트 제작과 상용 플랜트 핵심공정 개발, 실증 플랜트 건설과 일관공정 자동화시스템 구축 등을 거쳐 2015년부터 연간 2만~10만 톤의 리튬을 대량 생산하게 됩니다.

리튬은 하이브리드와 전기자동차, 휴대폰, 노트북 PC와 같은 이동용전자기기에 사용되는 2차 전지 원료와 차세대 핵융합 발전 원료 등으로 사용되는 전략 금속입니다.

http://article.joinsmsn.com/news/article/article.asp?total_id=4570206&ctg=1100

D-T Fusion

Li: 녹색광물. 전기차와 ESS의 2차전지에 사용됨.

"한국광물자원공사가 발표한 '리튬시장 최근 동향 및 전망'이라는 보고서에 의하면 2016년 4월 6일자 리튬 가격은 2015년 1월 대비 약 270% 상승했다. 집계가 시작된 2007년 이후 명목 가격으로는 최고점에 있으며 8~9년 전 대비 370% 인상된 상태다.
리튬의 가격이 천정부지로 치솟는 이유는 스마트폰 및 태블릿 등 IT 제품의 수요 덕분이다. 거기다 자동차 1대당 엄청난 양의 리튬이 사용되는 전기자동차 시장의 활성화가 리튬 가격의 인상을 더욱 부채질하고 있다."

전기자동차 및 재생에너지 분야의 성장으로 리튬 가격이 폭등하고 있다. 사진은 리튬 중 가장 많이 사용되는 탄산리튬.

WIKIPEDIA
The Free Encyclopedia

http://www.sciencetimes.co.kr/?news=%ec%8b%a0%ea%b8%b0%ed%9b%84%ec%b2%b4%ec%a0%9c%eb%a1%9c-%eb%85%b9%ec%83%89%ea%b4%91%eb%ac%bc-%eb%9c%ac%eb%8b%a4

D-T Fusion

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

- Fusion reaction rate as a function of position and time

$$R_{dt}(\vec{r},t) = N_d(\vec{r},t)N_t(\vec{r},t) < \sigma v >_{dt} (\vec{r},t)$$

- Fusion power density

$$P_{dt}(\vec{r},t) = R_{dt}(\vec{r},t)Q_{dt} = N_d(\vec{r},t)N_t(\vec{r},t) < \sigma v >_{dt} (\vec{r},t)Q_{dt}$$

D-D Fusion

$$d + d \rightarrow p + t + 4.1\,\text{MeV}$$
$$\rightarrow n + {}^3He + 3.2\,\text{MeV}$$

- **D-D fusion**

- Possessing a much smaller power density

→ requiring a larger size for a specified total fusion power production

- **Side reactions**

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

$$d + {}^3He \rightarrow p + \alpha + 18.3\,\text{MeV}$$

$$t + t \rightarrow 2n + \alpha + 11.3\,\text{MeV}$$

$${}^3He + {}^3He \rightarrow 2p + \alpha + 12.9\,\text{MeV}$$

$$t + {}^3He \rightarrow n + p + \alpha + 12.1\,\text{MeV}$$
$$\rightarrow d + \alpha + 14.3\,\text{MeV}$$

D-D Burn Modes

- **PURE-D Mode**

$$d + d \rightarrow p + t + 4.1\,\text{MeV}$$

Channel - *t*

$$\rightarrow n + {}^{3}He + 3.2\,\text{MeV}$$

Channel - ³*He*

$$R_{dd,t} = \boxed{\frac{N_d^2}{2}} < \sigma v >_{dd,t}$$

$$R_{fu} = N_a N_b < \sigma v >_{ab}$$

$$R_{dd,{}^3He} = \frac{N_d^2}{2} < \sigma v >_{dd,{}^3He}$$

$$< \sigma v >_{dd} = < \sigma v >_{dd,t} + < \sigma v >_{dd,{}^3He}$$

$$< \sigma v >_{dd,t} \approx < \sigma v >_{dd,{}^3He} \approx \frac{1}{2} < \sigma v >_{dd}$$

At temperatures of common interest

D-D Burn Modes

- To find the number of (x,y) combinations

	a_1	a_2	…	a_x	…	a_{Na}
b_1						
b_2						
…						
b_y				(a_x,b_y)		
…						
b_{Nb}						

Interaction between N_a a-type and N_b b-type particles

$$R_{ab} = N_a N_b < \sigma v >_{ab}$$

	a_1	a_2	…	a_x	…	a_{Na}
a_1						
a_2						
…						
a_x				(a_x,a_x)		
…						
a_{Na}						

Interaction between N_a a-type particles

$$R_{aa} = \frac{N_a(N_a - 1)}{2} < \sigma v >_{aa}$$

$$\approx \frac{N_a^2}{2} < \sigma v >_{aa}$$

D-D Burn Modes

- **Semi-Catalyzed-D cycle (SCAT-D Mode)**

The bred tritium consumed almost immediately

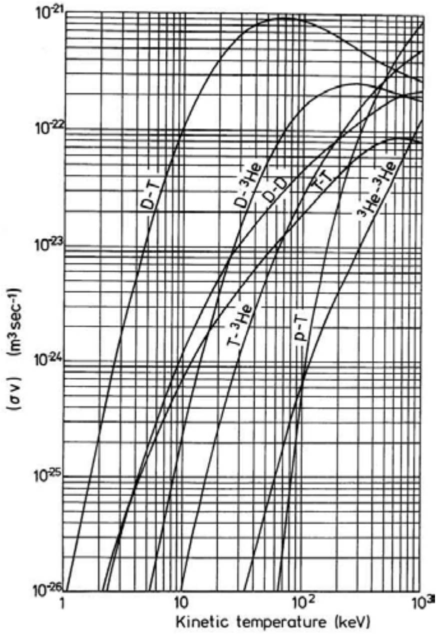
$$d + d \rightarrow t + p + 4.1\,\text{MeV}$$ **Channel - *t***

↘ reaction link

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

$$d + d \rightarrow {}^3He + n + 3.2\,\text{MeV}$$ **Channel - ^{3}*He***

$$5d \rightarrow 2n + {}^3He + \alpha + p + 24.9\,\text{MeV}$$



Providing $R_{dd,t} = R_{dt}$ (triton fusion burn at a rate equal to its production rate)

$$\frac{N_d^2}{2} < \sigma v >_{dd,t} = N_d N_t < \sigma v >_{dt}$$

$$\frac{N_t}{N_d} = \frac{1}{2}\frac{< \sigma v >_{dd,t}}{< \sigma v >_{dt}} \approx \frac{1}{4}\frac{< \sigma v >_{dd}}{< \sigma v >_{dt}}$$

The relative tritium concentration in the fusing plasma may be small at low-to-medium temperatures but will increase for higher temperatures.

D-D Burn Modes

- **Catalyzed-D cycle (CAT-D Mode)**

$$d + d \rightarrow t + p + 4.1\,\text{MeV}$$ **Channel - *t***

↘ reaction link

$$d + t \rightarrow n + \alpha + 17.6\,\text{MeV}$$

$$d + d \rightarrow {}^{3}He + n + 3.2\,\text{MeV}$$ **Channel - ^{3}*He***

↘ reaction link

$$d + {}^{3}He \rightarrow \alpha + p + 18.3\,\text{MeV}$$

$$6d \rightarrow 2n + 2\alpha + 2p + 43.2\,\text{MeV}$$

D-D Burn Modes

- **General D-D initiated fusion linkage processes**

$$d + d \rightarrow t(1.0) + p(3.1)$$

$$d + t \rightarrow n(14.1) + \alpha(3.5)$$

$$t + t \rightarrow n(5.0) + n(5.0) + \alpha(1.3)$$

$$t + {}^{3}He \rightarrow p(5.7) + \alpha(1.3) + n(5.1)$$

$$d + d \rightarrow {}^{3}He(0.8) + n(2.4)$$

$$d + {}^{3}He \rightarrow \alpha(3.7) + p(14.6)$$

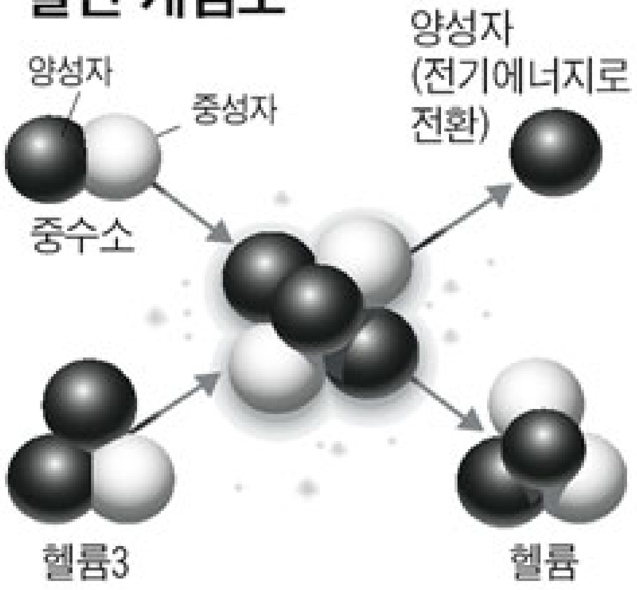
$${}^{3}He + {}^{3}He \rightarrow p(5.7) + p(5.7) + \alpha(1.4)$$

The connection reaction linkages vary with temperature and density.

D-^{3}He Fusion

$$d + {}^{3}He \rightarrow p + \alpha + 18.3\,\mathrm{MeV}$$

헬륨3를 이용한 핵융합 발전 개념도



헬륨3 차세대 핵융합 발전의 연료.
헬륨3의 원자는 양성자 2개와 중성자 1개로 이뤄져 있으며, 중수소(양성자 1개 중성자 1개)와 핵융합을 하면 정상적인 헬륨 원자(양성자 2개, 중성자 2개)가 되면서 강한 에너지를 가진 양성자를 방출한다.

1000MW급 발전소 가동을 위한 연료별 소모량 단위:kg/day

석탄	8,640,000
우라늄(235)	3
헬륨3	0.2

D-^{3}He Fusion

- **An attainable "clean" fusion reaction, direct energy conversion**

- Tritium, neutron: problems of radiological safety, first wall endurance, shielding and induced radioactivity

- **Higher reaction temperature required**
- **More severe Bremsstrahlung radiation**
- **Scarce ^3He: $^3He/(^3He+^4He) \sim 10^{-6}$**

supply by nuclear decay of tritium

$$t \rightarrow {}^3He + \beta^- + 18.6\ \mathrm{keV}$$

supply by d-d fusion reaction

$$d + d \rightarrow {}^3He + n + 3.2\ \mathrm{MeV}$$

Lunar Rock

D-^{3}He Fusion

SCIENCE

Mining The Moon

An Apollo astronaut argues that with its vast stores of nonpolluting nuclear fuel, our lunar neighbor holds the key to Earth's future.

BY HARRISON H. SCHMITT
ILLUSTRATION BY PAUL DIMARE

Apollo 17 astronaut Harrison Schmitt left the moon 32 years ago with 244 pounds of rocks and an abiding desire to see humankind continue its exploration of space. Now, in an exclusive essay for POPULAR MECHANICS, Schmitt explains why the time is right for America to return.

FUTURE MINERS: Robotic equipment would scrape and refine lunar soil. Helium-3 would be sent to Earth aboard a future space shuttle or perhaps be shot from an electric rail gun.

56 OCTOBER 2004 | WWW.POPULARMECHANICS.COM

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D-^{3}He Fusion

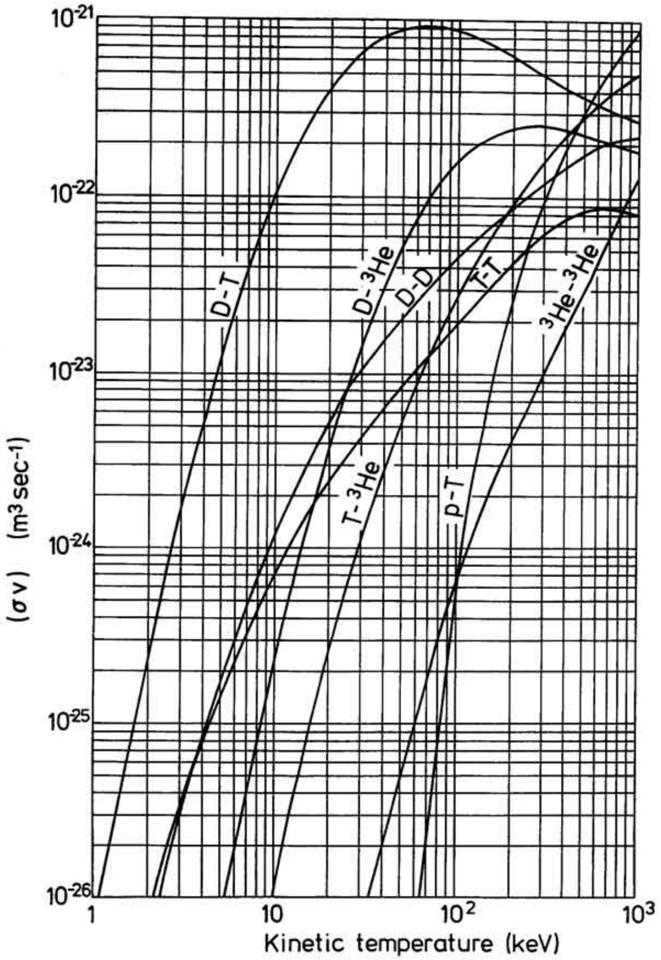
$$d + {}^3He \rightarrow p + \alpha + 18.3\,\text{MeV}$$

unclean side reactions

$$d + d \rightarrow t + p + 4.1\,\text{MeV}$$

$$d + d \rightarrow {}^3He + n + 3.2\,\text{MeV}$$

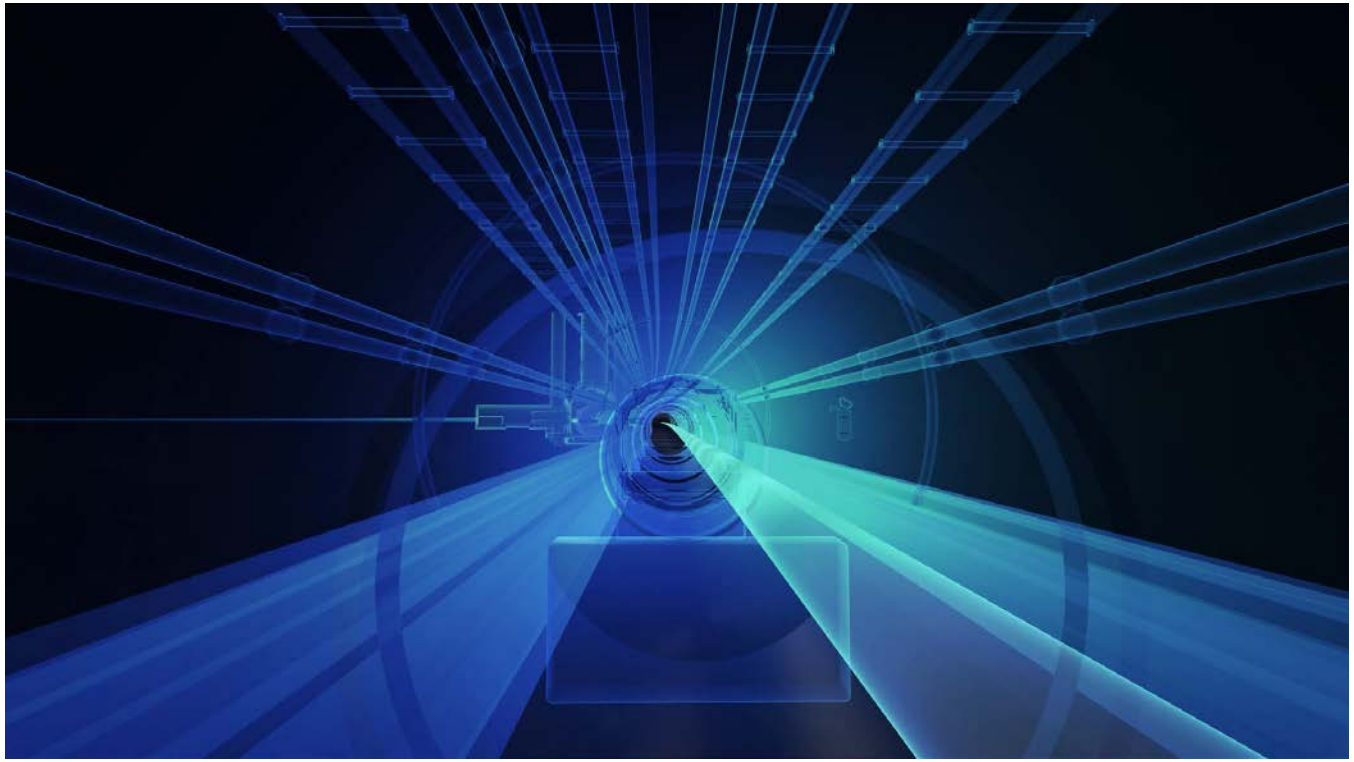
Control on high temperature and ^{3}*He* and *d* fuel ions for cleanliness



$$\frac{R_{d^3He}}{R_{dd,t}} = 2\frac{<\sigma v>_{d^3He}}{<\sigma v>_{dd,t}}\frac{N_{^3He}}{N_d} \qquad \frac{R_{d^3He}}{R_{dd,^3He}} = 2\frac{<\sigma v>_{d^3He}}{<\sigma v>_{dd,^3He}}\frac{N_{^3He}}{N_d}$$

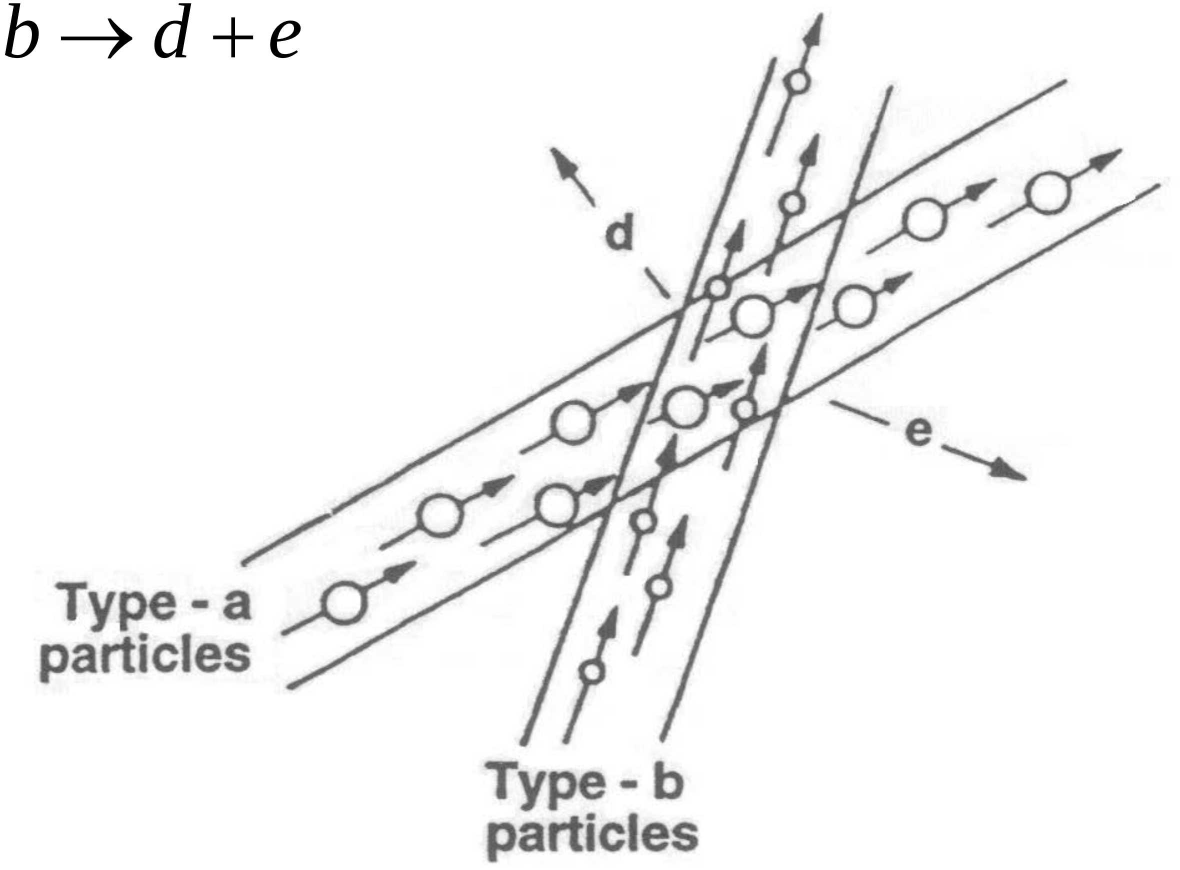
How to realise fusion on earth?

Beam target Fusion



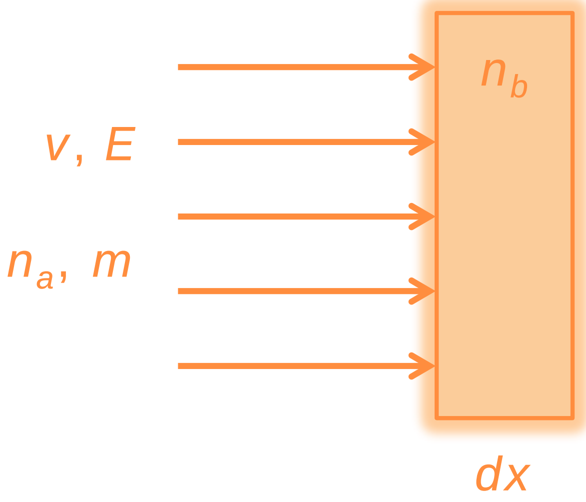
Beam target Fusion

$$a + b \rightarrow d + e$$



Beam target Fusion

- **Beam-target collisions (Binary interactions)**



- For fixed target

$$m = m_a, \quad v = v_a, \quad E = m_a v_a^2 / 2$$

- For moving target

$$m = m_r, \quad v = |v_a - v_b|, \quad E = E_{CM}$$

$$dn_a = -\sigma_{ab}(E) n_a n_b dx$$

- **Fusion cross section for low energy $E_{CM} < U(R_0)$ by quantum mechanical tunneling process:**

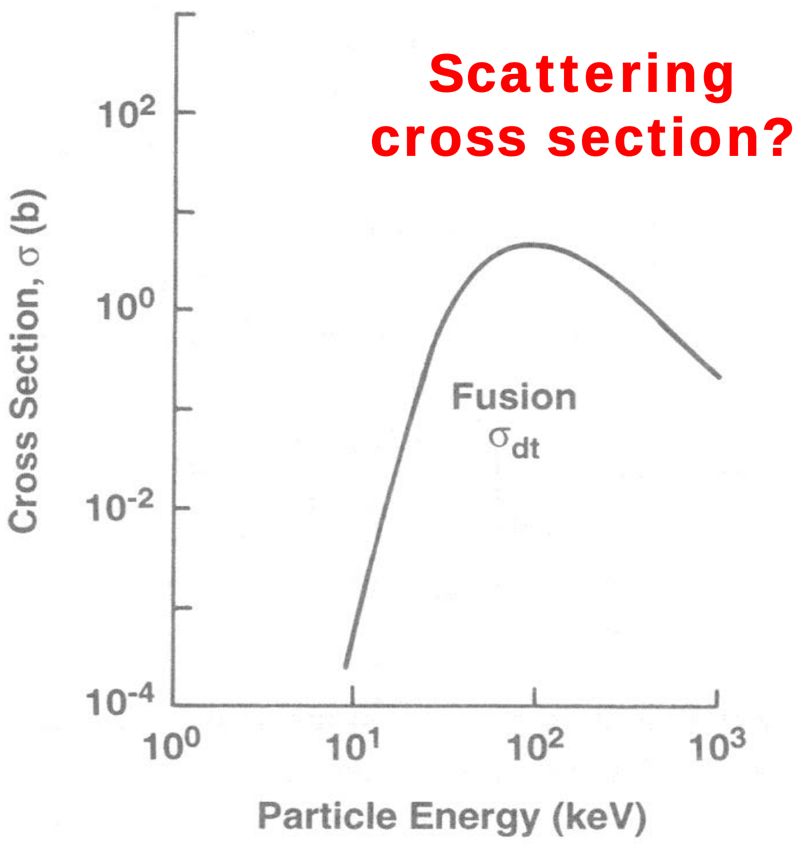
$$\sigma_{ab}(E) = \frac{A}{E} e^{-B/\sqrt{E}}$$

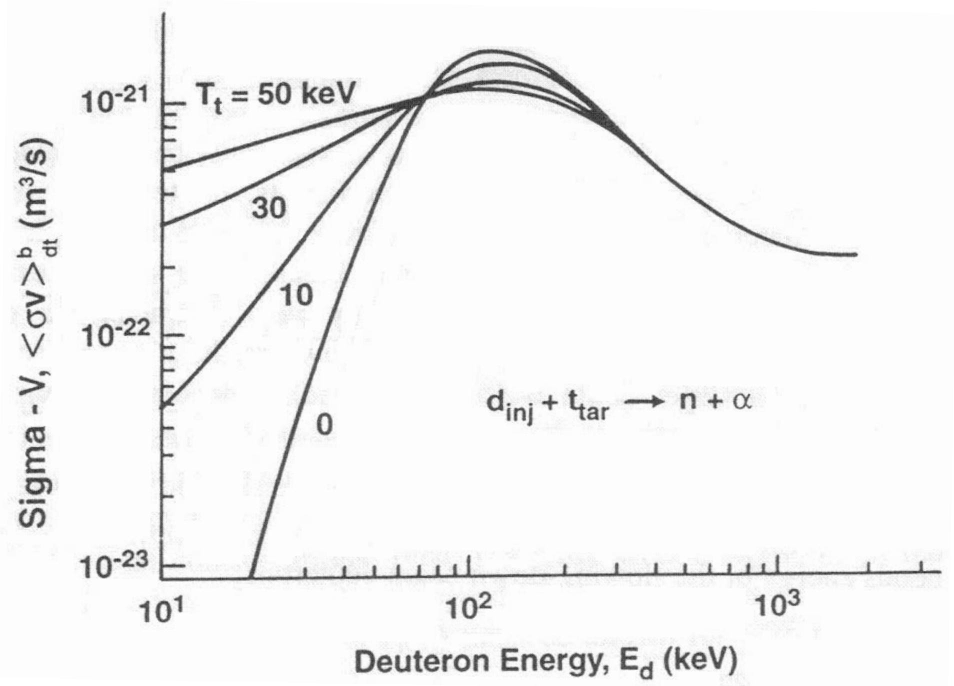
Gamow theory (1938)

$$A = const., \quad B = 2^{-1/2} \pi m_r^{1/2} Z_a Z_b e^2 / h\varepsilon_0$$

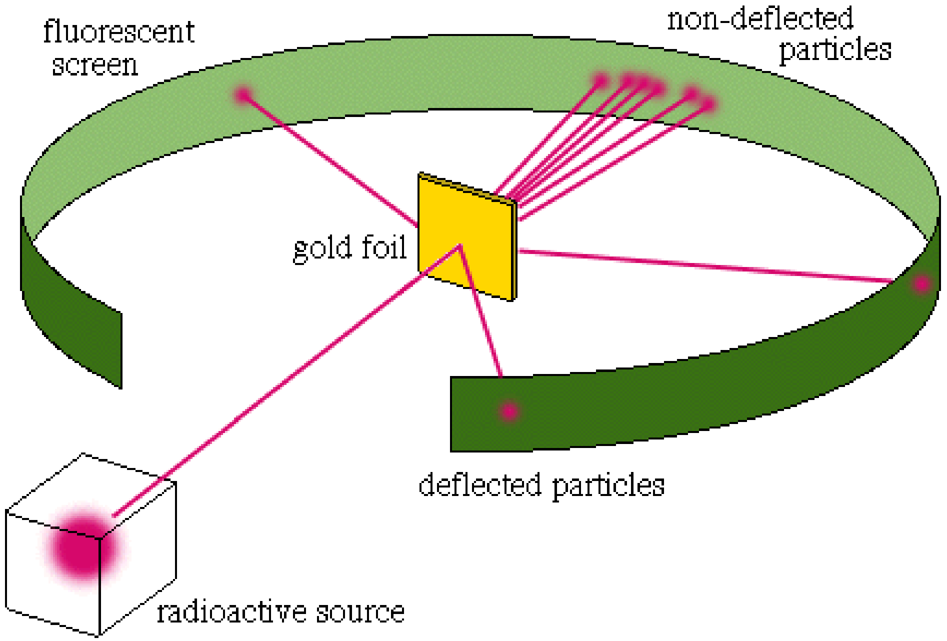
Beam target Fusion

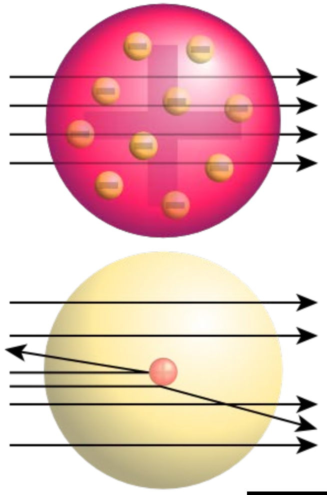
- **Beam-target collisions (Binary interactions)**



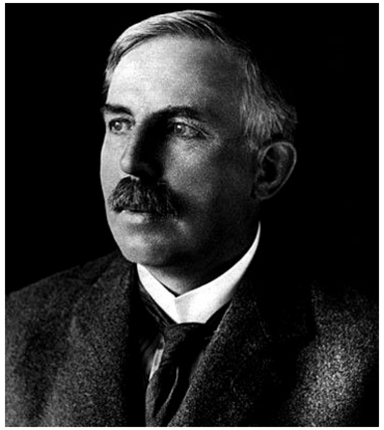


Rutherford Scattering



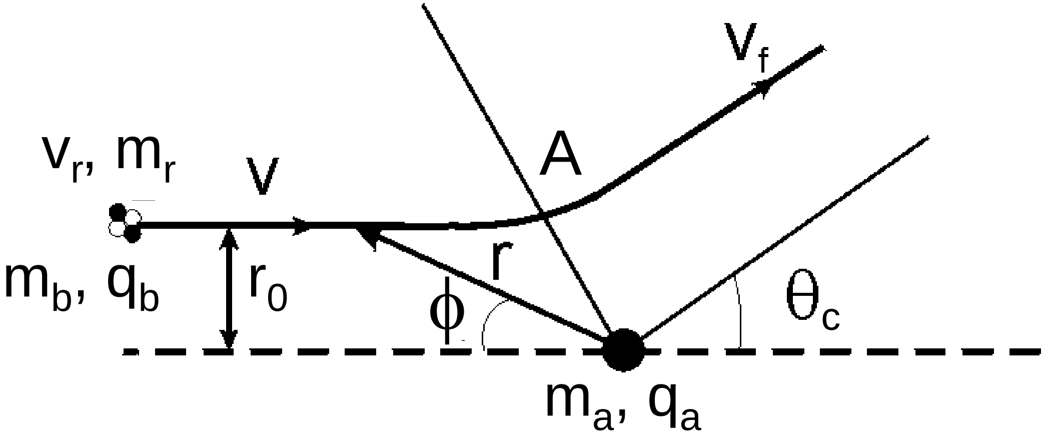


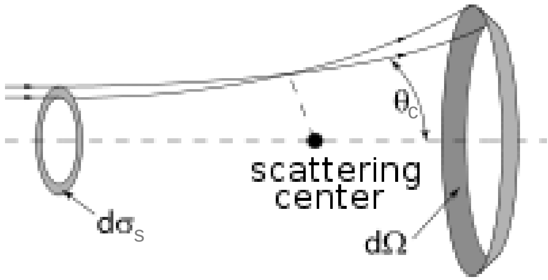
"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." by Rutherford



Ernest Rutherford
(1871-1937)
Nobel prize in Chemistry 1908

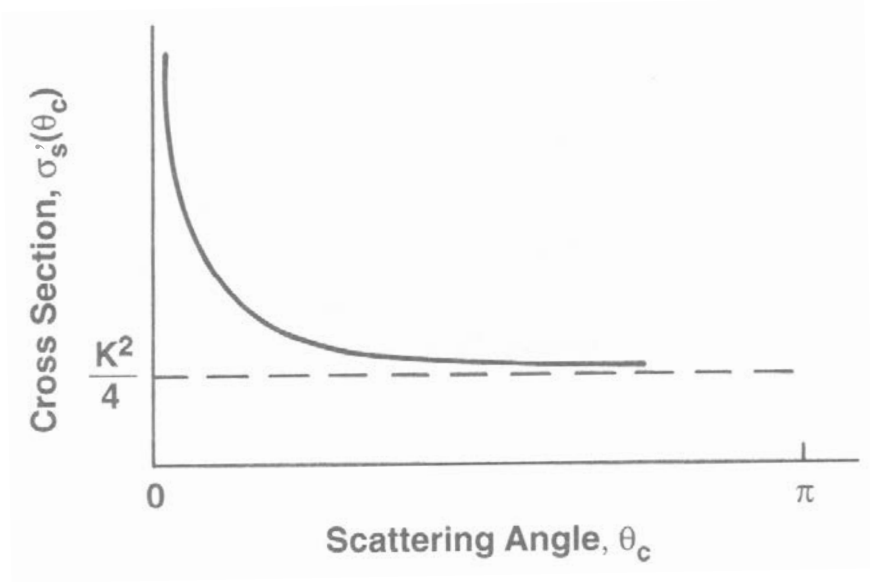
Coulomb Scattering Cross Section





$$\sigma_s = \pi K^2 \left\{ \left[\sin\left(\frac{\theta_{min}}{2} \right) \right]^{-2} - 1 \right\}$$

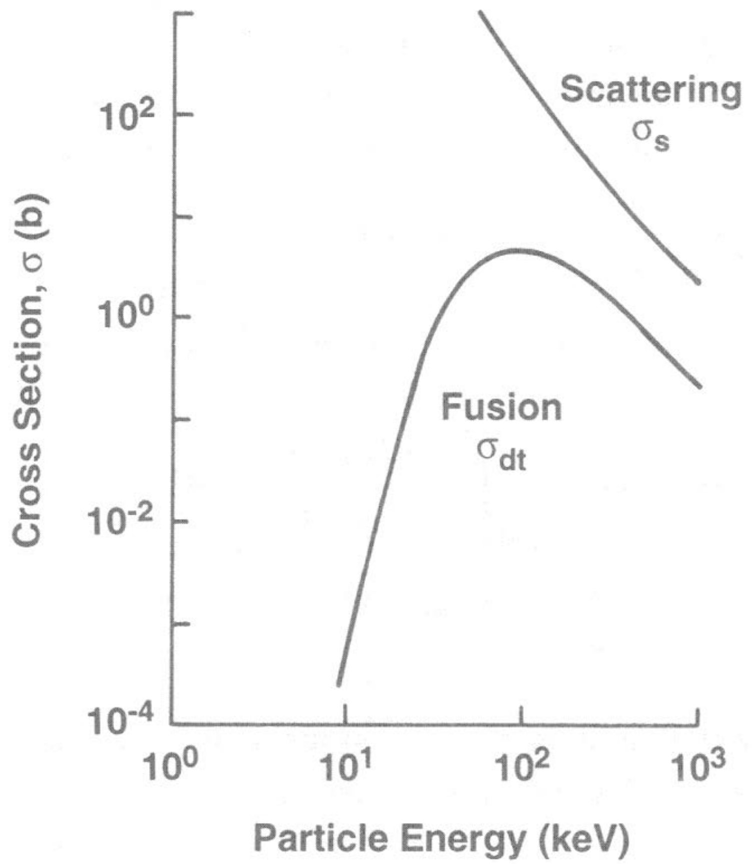
$$\theta_{min} = 2\tan^{-1}\left(\frac{K}{\lambda_D} \right) \qquad \lambda_D = \left(\frac{\varepsilon_0 k T_e}{N e^2} \right)^{1/2}$$



Coulomb Scattering Cross Section

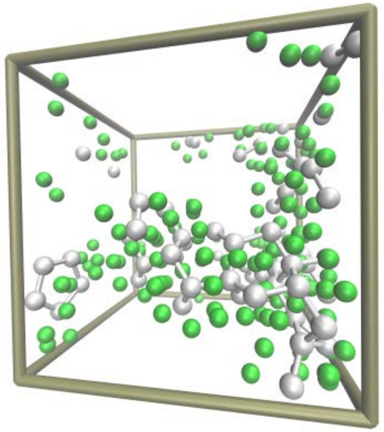
$$\sigma_{scatt} >> 100\sigma_{dt}$$

- loss energy >> fusion energy
  - ionisation, heating the target, bremsstrahlung radiation, etc
- Projectiles slowed down to energies far below the Coulomb barrier (370 keV in DT) rendering further fusion reactions most unlikely
- Fusion by beam-target collisions are not proper for practical energy-producing fusion reactors.



Confinement needed!

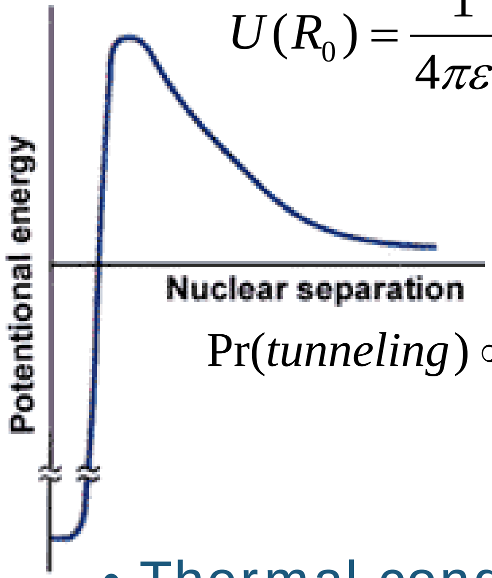
Confinement for Fusion



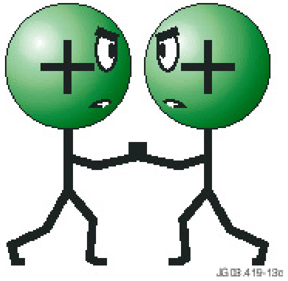
http://rumd.org/
http://blog.naver.com/PostView.nhn?blogId=ofgrnkqn&logNo=90145273295&redirect=Dlog&widgetTypeCall=true
http://desert.tistory.com/1991

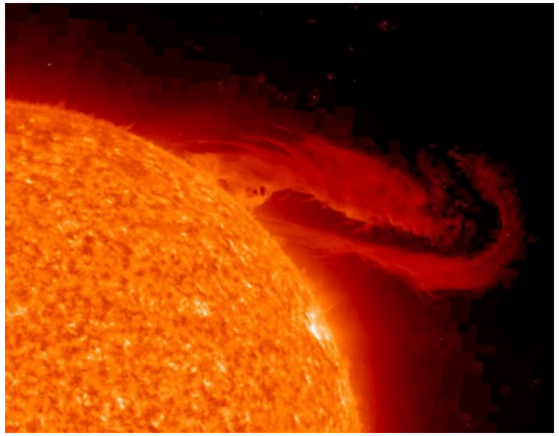
Realisation of Nuclear Fusion

$$U(R_0) = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{R_0} \sim 0.4\ \text{MeV for } d, t, p$$



$$\Pr(tunneling) \propto \frac{1}{v_r}\exp[-\gamma\frac{q_a q_b}{v_r}]$$





- Thermal conditions with high temperature needed for the high fusion reaction rate
- A sufficiently high temperature plasma needed to sustain in a practical reaction volume for a sufficiently long period of time.

Thermonuclear?

Thermonuclear fusion in a confined way:
Main approach to develop fusion energy