The Physics of Inertial Confinement Fusion at the National Ignition Facility

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DEPARTMENT OF PHYSICS

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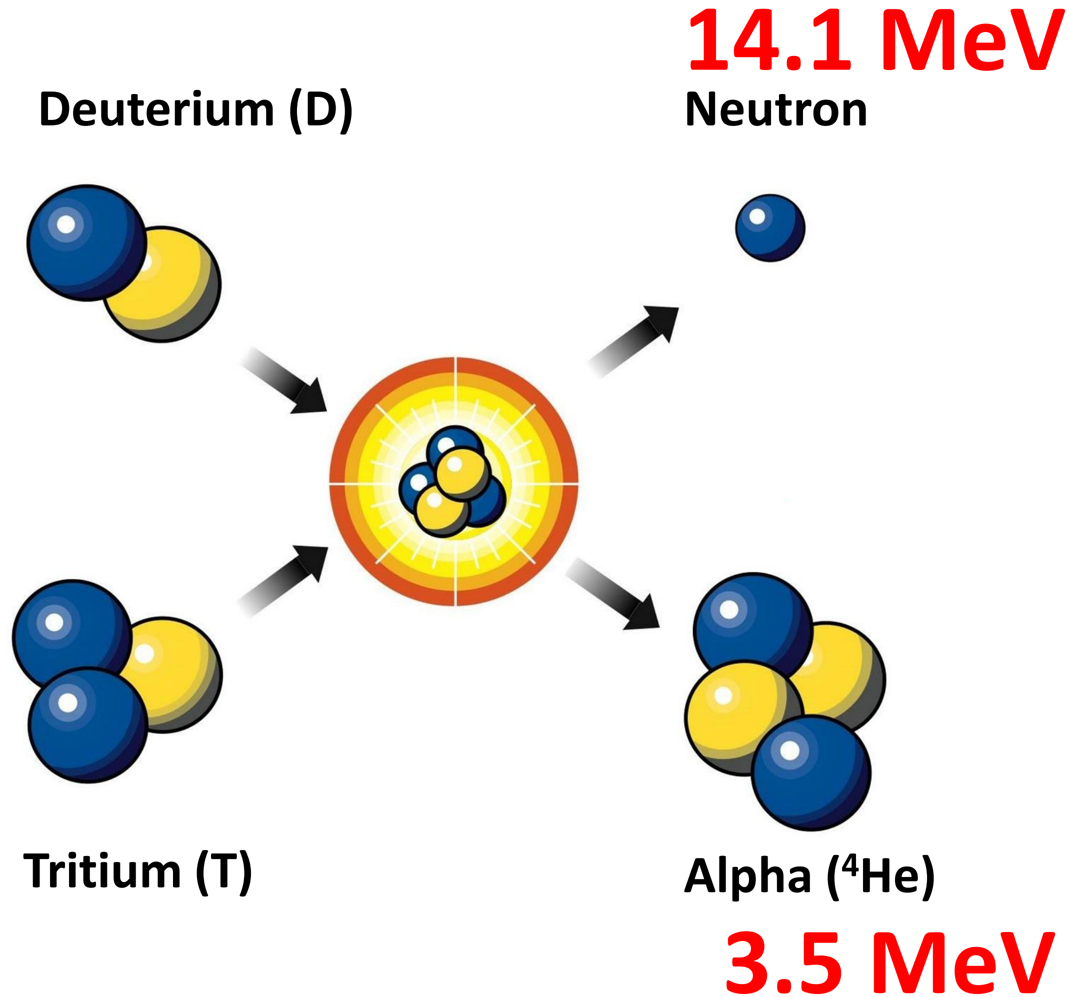
Academic Background

- Undergraduate: Rowan University
  - B.S. Physics
  - B.A. Mathematics
- Gap Year: Brookhaven National Laboratory
  - SULI Internship Program
- 3rd Year Grad Student: OSU
  - Plasma Physics
  - Particle In Cell Simulations
  - Machine Learning

What is Nuclear Fusion?

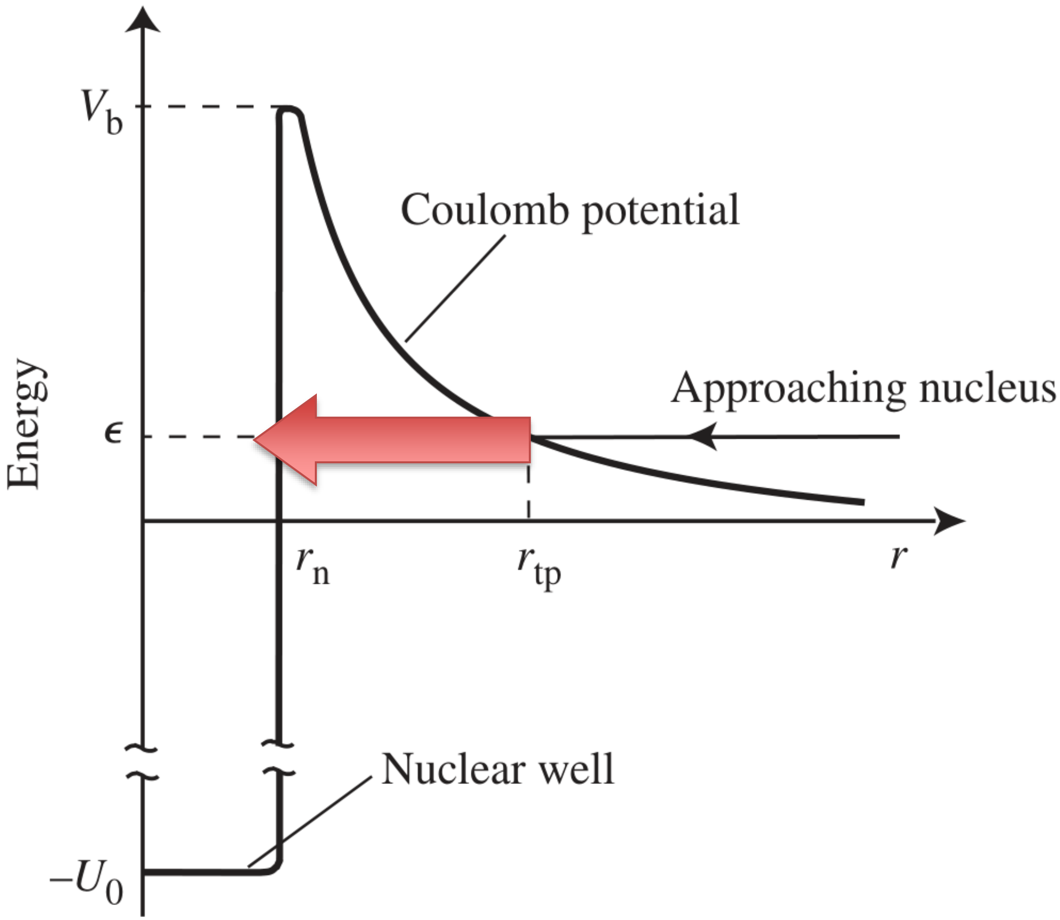
- Two lighter nuclei combine to form heavier nucleus
- $Q = (\Delta m)c^2$
  - $\boldsymbol{Q_{DT}}$ =17.6 MeV
- Compare DT and Coal:
  - DT: 300 GJ/g
  - Coal: 30 kJ/g
  - Factor of 10 Million!



https://interestingenergyfacts.blogspot.com/2010/04/nuclear-fusion-facts.html

How to Fuse Nuclei

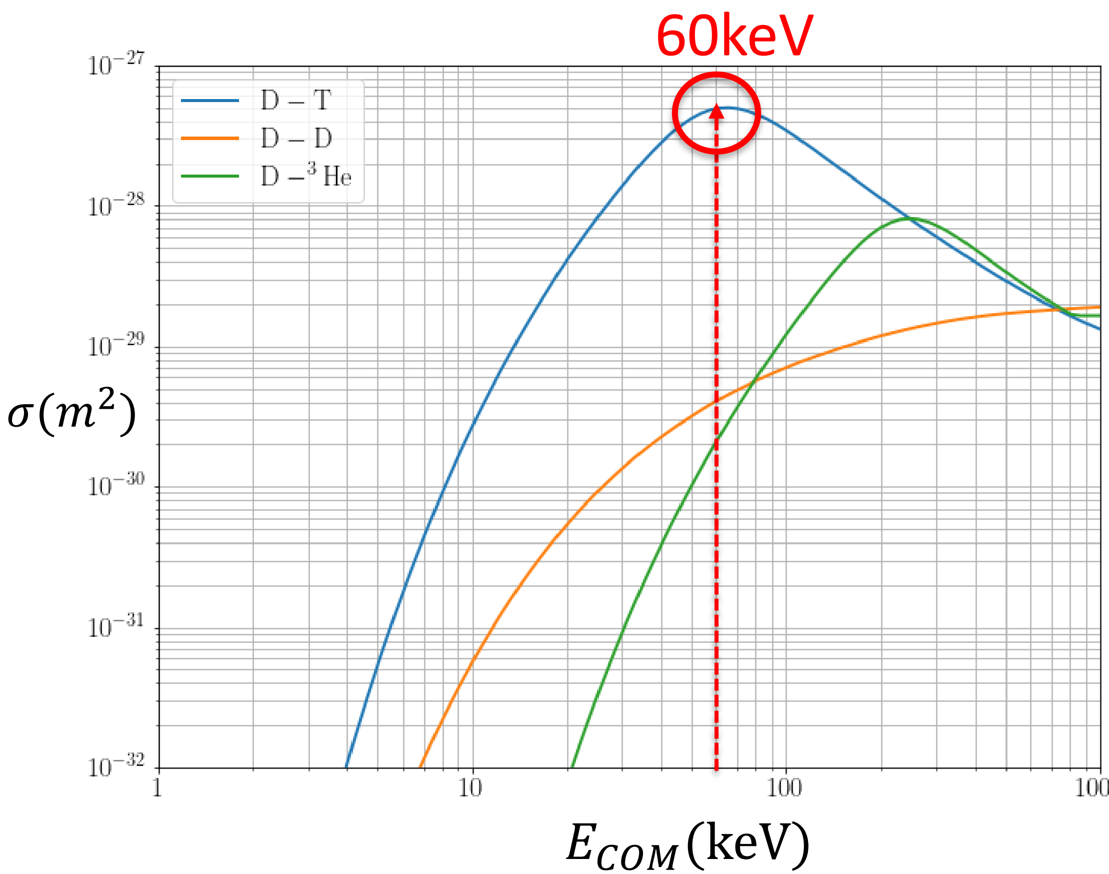
- Need to overcome repulsive coulomb barrier
- $V_b \approx 1\ MeV$
  - 500x hotter than solar core
- Can Tunnel through barrier Quantum Mechanically



S. Atzeni, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter* (2004)

Why DT Fusion?

- High Fusion Cross Section (FCS): σ
  - Dependent on Geometric Cross Section and Tunneling Probability
- Low Temperature
  - $E_{COM} \sim 60keV$
  - T~10 keV
  - 1 keV ~ 11 Million K



https://scipython.com/blog/plotting-nuclear-fusion-cross-sections/

Lawson Criterion

- Conditions for sustained fusion?
  - n: Number density high enough for frequent collisions
  - τ: Long confinement time for fuel to fully burn

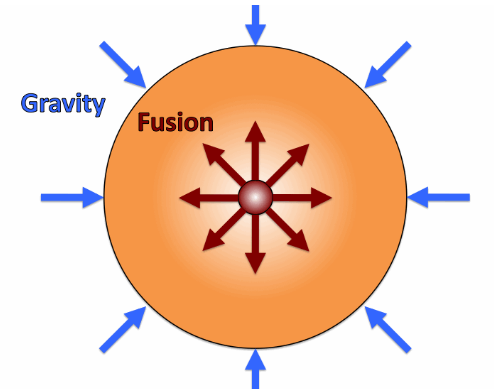
$$n\tau > 10^{15} s/cm^3$$

- for DT fusion

$$n\tau > \frac{12k_BT}{\langle\sigma v\rangle Q}$$

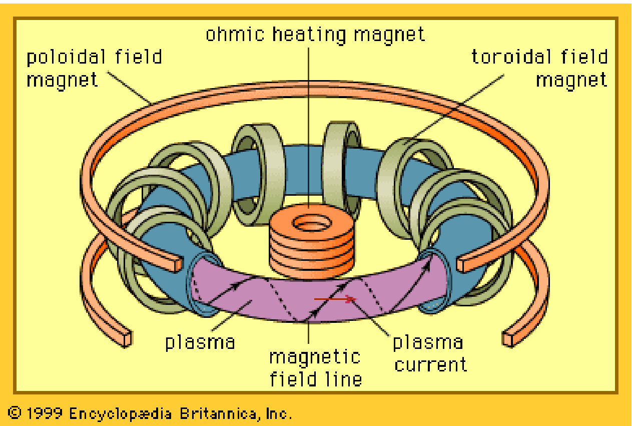
- T = Temperature
- Q = Energy Released
- $\langle\sigma v\rangle$ = Fusion Cross Section integrated over Maxwell-Boltzmann Distribution

Types of Confinement



http://large.stanford.edu/courses/2011/ph241/olson1/

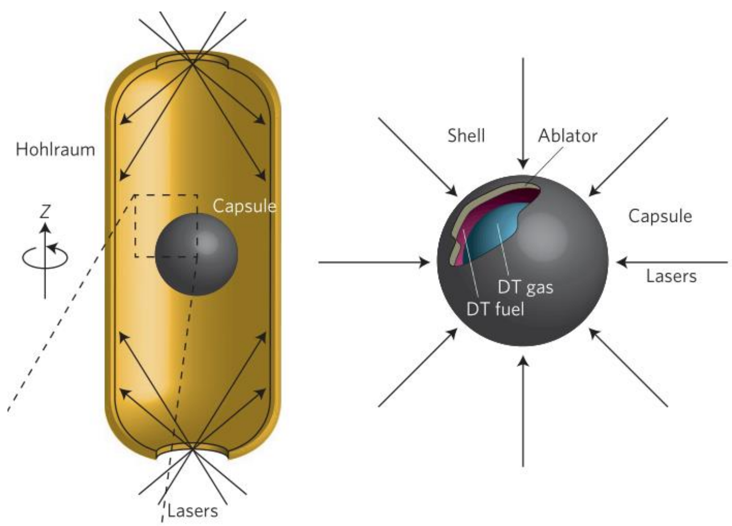
Gravitational



Magnetic

https://www.britannica.com/technology/fusion-reactor/Principles-of-magnetic-confinement

Inertial (ICF)



Nature Phys **12**, 435–448 (2016)

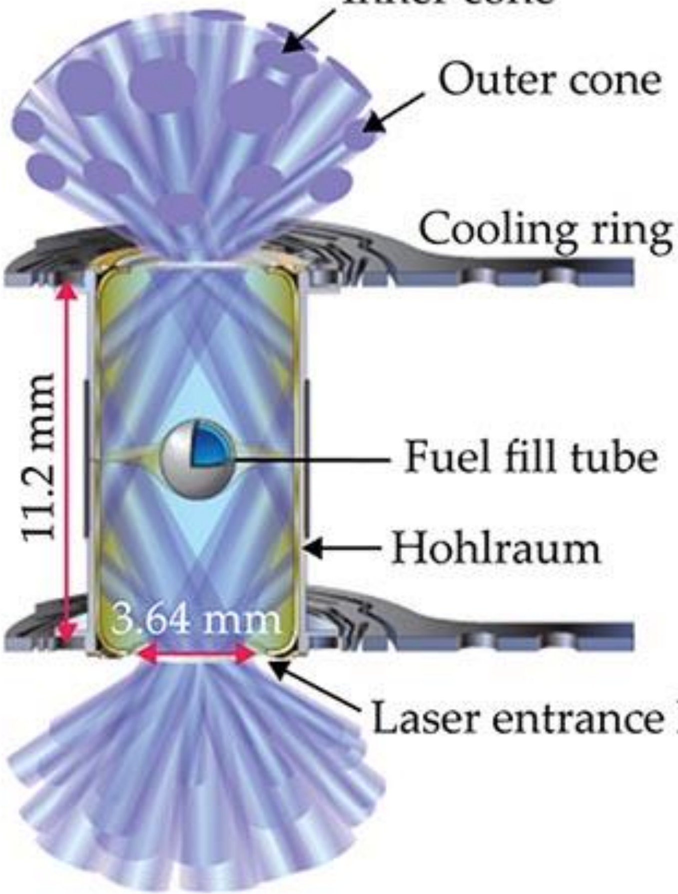
Indirect Drive

Direct Drive

Hohlraum Temperature

- Laser enters through Laser Entrance Hole (LEH)
- Heats inner surface of cylinder
- $I \sim \sigma_{SB} T^4$
  - $I = \frac{P \sim 500\ TW}{A_H \sim 1 cm^2} \sim 10^{15} W/cm^2$
  - $T_r \sim 250\ eV$

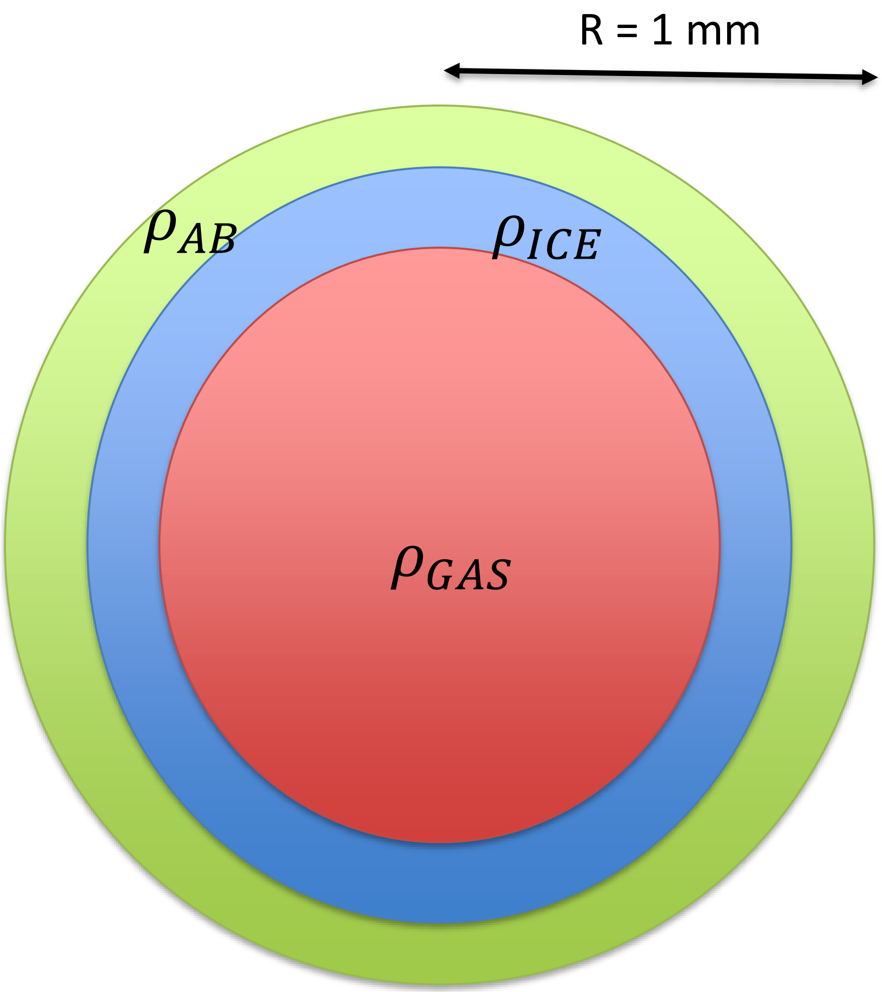
- Want High Temperature
  - Small Hohlraum
  - Small LEH



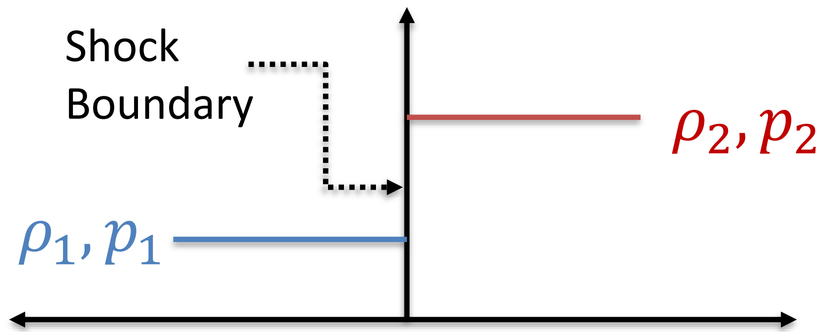
Nature **601**, 542–548 (2022)

Capsule

- Outer Shell: Ablator
  - Vaporized by Laser
- Inner Shell: DT Ice
  - T~18K
  - Most of Fuel Mass
- Inner Core: DT gas
  - Low Density
  - Reaches Highest Temperature



1D Hydrodynamics



- Shock Waves Drive Compression
  - Sharp pressure changes from short pulse laser
- Euler Equations of Hydrodynamics
  - mass, momentum, energy
- Ex) Want $\frac{V_2}{V_1} = \frac{1}{4}$:
  - $\frac{p_2}{p_1} \rightarrow \infty$ for 1 shock!
  - $\frac{p_2}{p_1} \approx 10$ isentropically

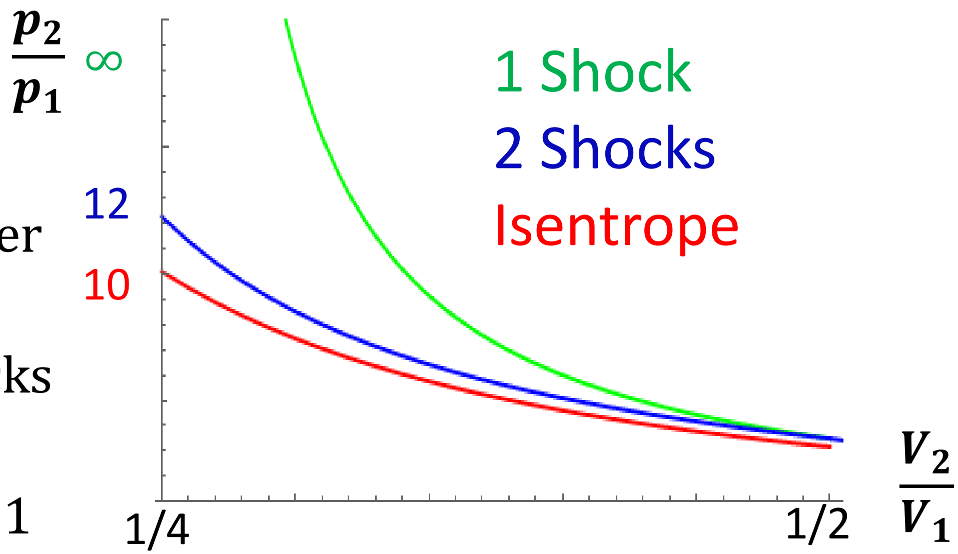
Specific Volume $V \equiv \frac{1}{\rho}$

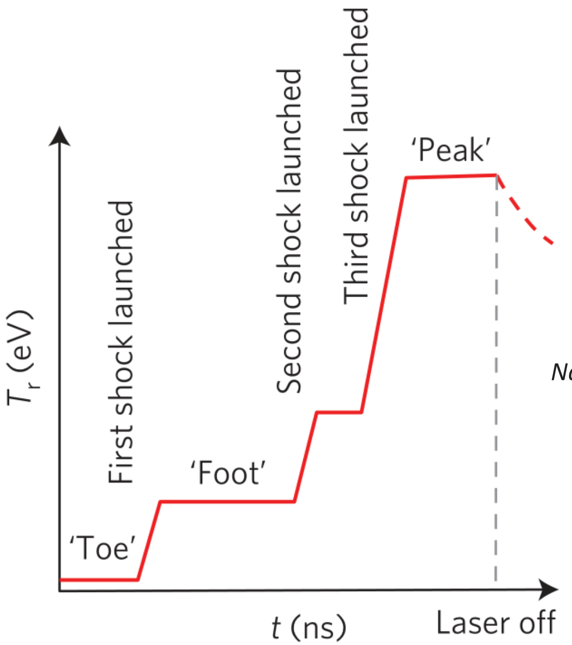
Shock Compression $$\frac{p_2}{p_1} = \frac{4 - V_2/V_1}{4V_2/V_1 - 1}$$

Isentropic Compression $$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{5/3}$$

Shocks

- Several Weak Shocks better than One Strong Shock
- Laser pulse tuned so shocks converge at center
- Isentrope Parameter $\alpha > 1$
  - Strong Shocks Increase
  - Want to minimize

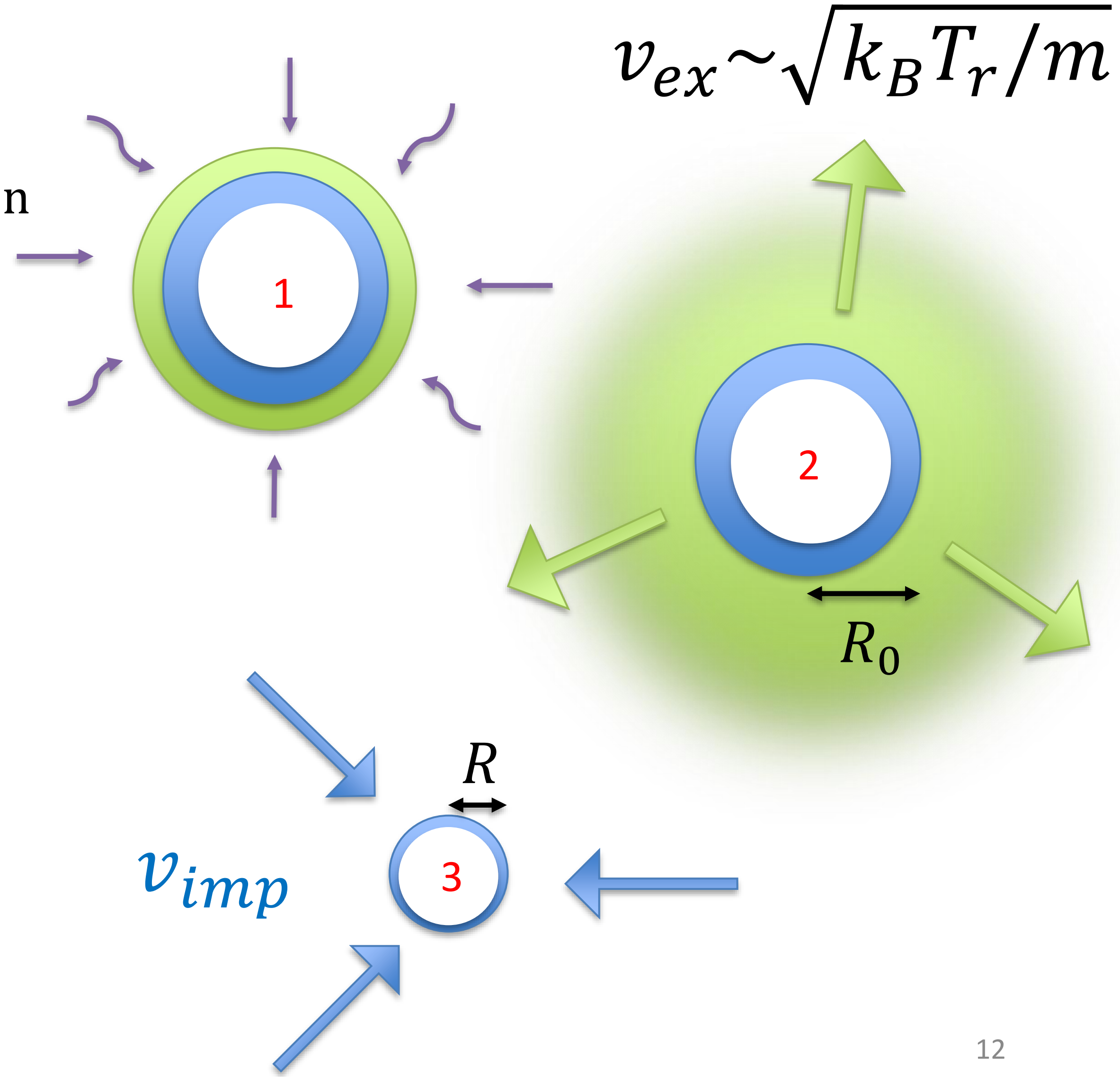




Nature Phys **12**, 435–448 (2016)

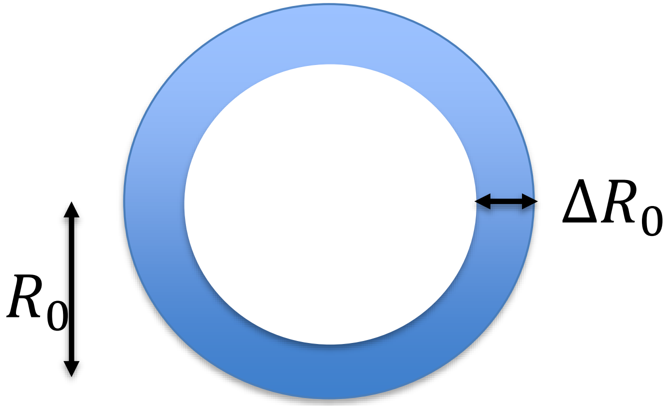
Shell Ablation

- Momentum Conservation
- (1) X-rays heat Ablator
  - Shell gets vaporized
- (2) Material ejected
  - outward
  - speed: v_{ex}
- (3) Implosion of shell
  - inward
  - speed: v_{imp}



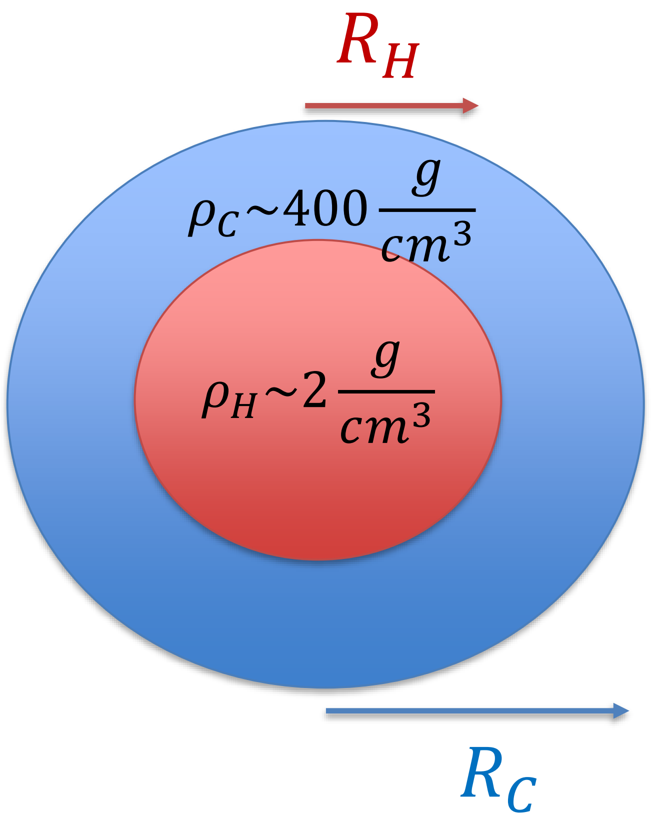
Spherical Rocket

- 1D Rocket Model
  - $M\frac{dv_{imp}}{dt} = v_{ex}\frac{dM}{dt} \rightarrow v_{imp} = v_{ex}\ln\left(\frac{M_0}{M}\right)$ Standard Rocket Equation
  - Radius of shell changes as fuel implodes inwards
- Implosion Velocity Scaling
  - $v_{imp} \sim v_a A$
  - Aspect Ratio: $A \approx \frac{R_0}{\Delta R_0}$
    - Thin shell drives faster implosions
  - Ablation Velocity: v_a
    - speed at which shell recedes
    - related to hohlraum temperature



Ignition and Burn

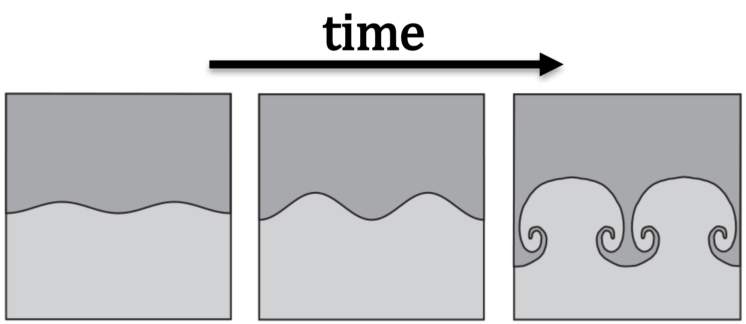
- Kinetic Energy of Imploding Shell goes to Internal Energy of DT Fuel.
  - $\mathrm{KE} = \frac{1}{2} M v_{imp}^2$
- Ignition Condition: $n\tau > \frac{10^{15} s}{cm^3}$
  - $n\tau = \frac{\rho}{m} \frac{R}{v_{th}} \sim \rho_C R_C$: in $\frac{g}{cm^2}$
- How to Quantify how much is burned?: Φ
  - Burn Efficiency: $\Phi \equiv \frac{\rho R}{\rho R + H_B}$
  - H_B is the burn parameter



Gain and Yield

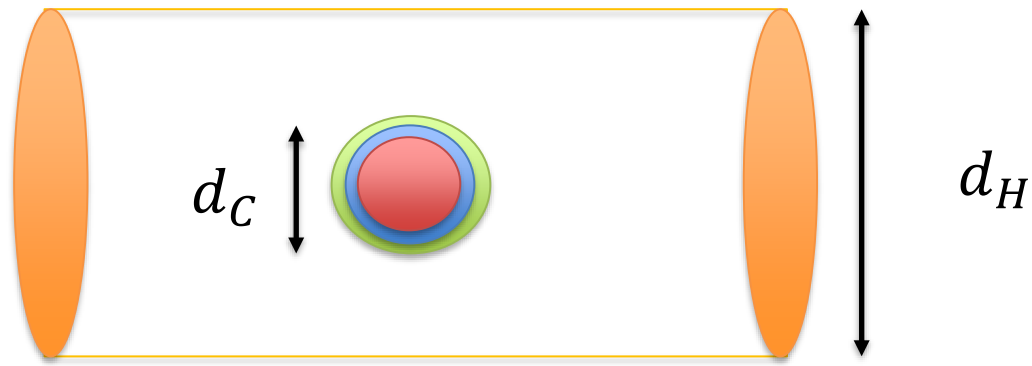
- Given ρR and T_H, we know fraction of fuel that gets burned Φ
  - $\Phi \equiv \frac{\rho R}{\rho R + H_B}$
- Alpha Particles cause heating:
  - $\mathrm{Q} = 3.5$ MeV per DT pair or 67 MJ/mg
- Multiply by total fuel mass M_f
- Fusion Energy Yield in MJ is "Y"
  - $Y = M_f Q \Phi$
- Gain: $G \equiv \frac{Y}{E_L}$
  - E_L is the laser energy on target

Instabilities and Symmetry

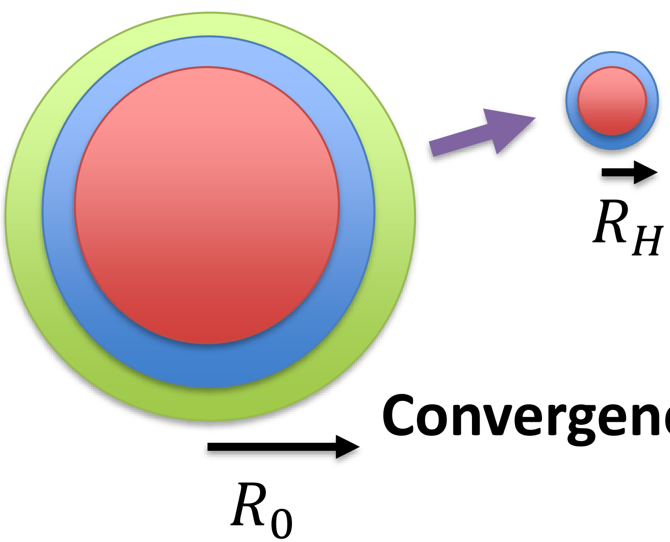


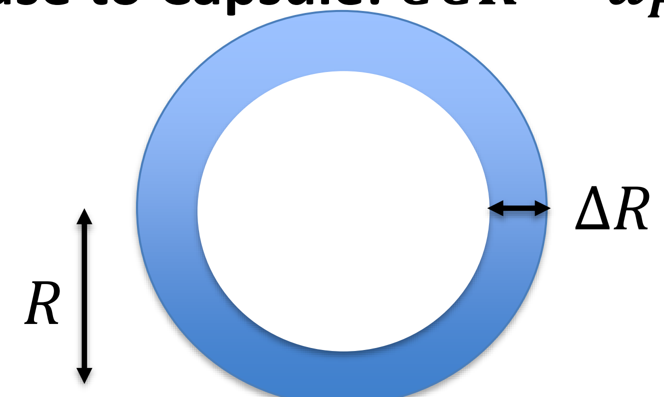
S. Atzeni, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter* (2004)

Rayleigh-Taylor Instability



Case to Capsule: $CCR = d_H/d_C$





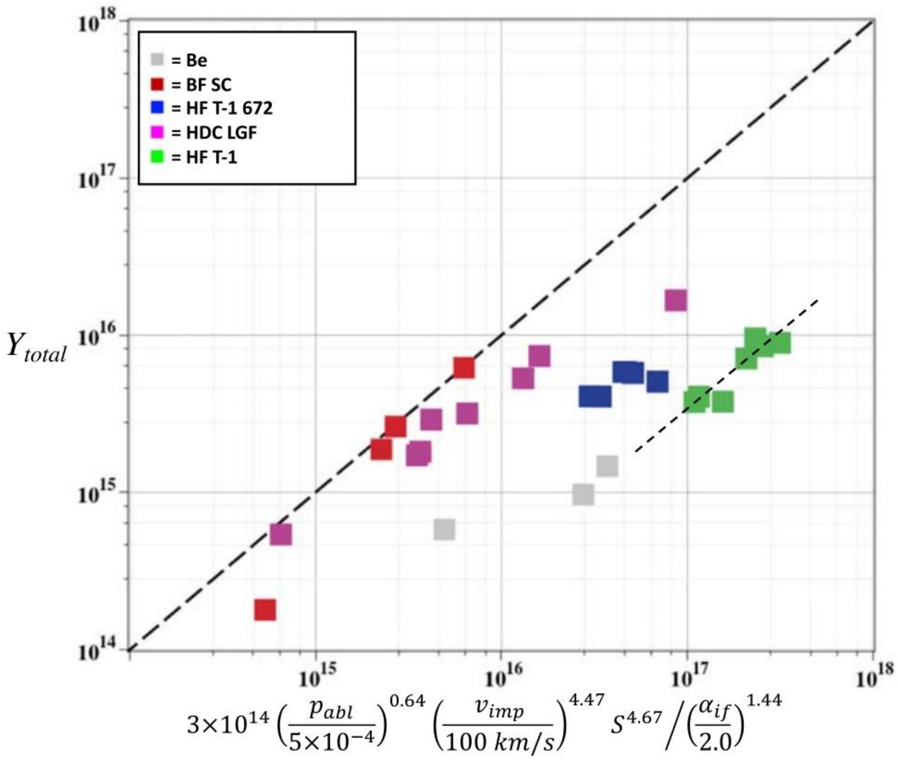
Convergence: $C \equiv R_0/R_H$

Aspect Ratio: A $\equiv R/\Delta R$

Neutron Yield Scaling

$$Y \sim P_{abl}^{0.64} \frac{v_{imp}^{4.47}}{\alpha^{1.44}} S^{4.67}$$

- P_{abl}: Ablation Pressure
  - Laser Energy
- v_{imp}: Implosion Velocity
  - Aspect Ratio
- S : Scale
  - Mass and Radius
- α : Isentrope Parameter
  - Laser Pulse Profile

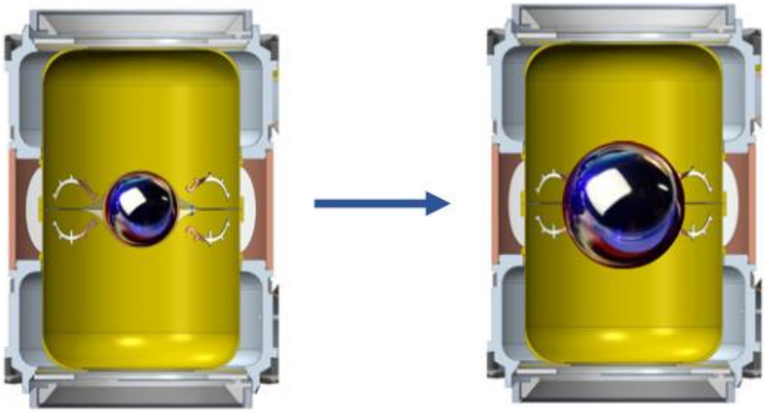


Plasma Phys. Control. Fusion 61 (2019)

Hybrid-E Campaign

- High Yield Big Radius Implosion Design
  - Increased Scale of NIF capsules ~15%
  - Kept Hohlraum Size Same
  - Differences in P_{abl}, v_{imp}, α negligible
- N170827 (HDC Campaign)
  - $R \approx 910\ \mu m$
  - $Y = 0.053$ MJ
- N210207 (HYBRID-E Campaign)
  - $R \approx 1050\ \mu m$
  - $Y = 0.174$ MJ
- Over 3x increase in yield, scaling predicts 2x increase
  - Scaling works best within same campaign

Phys. Plasmas 26, 052704 (2019)



$$\frac{Y_{21}}{Y_{17}} \sim \left(\frac{R_{21}}{R_{17}}\right)^{4.67} = (1.15)^{4.67} \approx 2$$

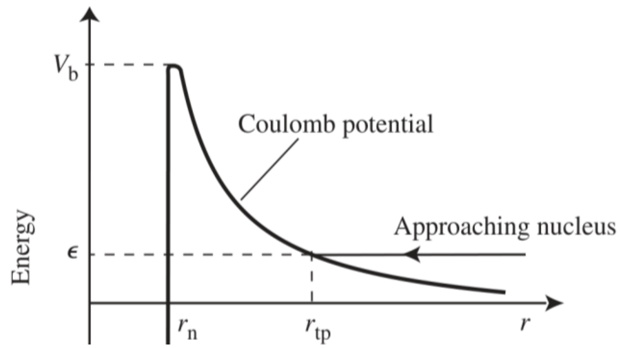
Conclusion

- DT most viable candidate for controlled fusion
- Physical Considerations
  - Laser Energy, Hohlraum/Capsule Size
- Engineering Considerations
  - Capsule Smoothness, Laser Efficiency
- N210207->N210808 Shot
  - 8x gain increase: same capsule size
  - mainly due to engineering advances
- Future of NIF
  - N210808->N221204 had G = 0.72 -> 1.5
  - N221204->N23???? has G=1.5 -> ???
    - 8% thicker ablator, 8% increase in laser energy
    - Symmetry Improvements

References

1. S. Atzeni, The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter, International Series of Monographs on Physics (Clarendon Press, 2004)
2. S. Pfalzner, An Introduction to Inertial Confinement Fusion (CRC Press, 2006)
3. O. Hurricane et al., Beyond alpha-heating: driving inertially confined fusion implosions toward a burning-plasma state on the national ignition facility, Plasma Physics and Controlled Fusion 61, 014033 (2019)
4. R. Betti and O. Hurricane, Inertial-confinement fusion with lasers, Nature Physics 12, 435 (2016)
5. A. Zylstra et al., Burning plasma achieved in inertial fusion, Nature 601, 542 (2022)
6. H. Abu-Shawareb et al. (Indirect Drive ICF Collaboration), Lawson criterion for ignition exceeded in an inertial fusion experiment, Phys. Rev. Lett. 129, 075001 (2022)
7. A. L. Kritcher et al., Achieving record hot spot energies with large hdc implosions on nif in hybrid-e, Physics of Plasmas 28, 072706 (2021)
8. S. Le Pape et al., Fusion energy output greater than the kinetic energy of an imploding shell at the national ignition facility, Phys. Rev. Lett. 120, 245003 (2018)
9. O. Hurricane et al., Approaching a burning plasma on the nif, Physics of Plasmas 26, 052704 (2019)
10. A. L. Kritcher et al., Design of an inertial fusion experiment exceeding the lawson criterion for ignition, Phys. Rev. E 106, 025201 (2022)
11. IAEA Webinar Explores NIF’s Ignition and Energy Gain Breakthroughs (llnl.gov)

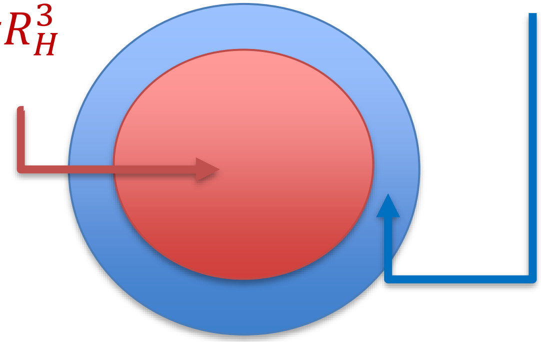
Tunneling Coulomb Barrier



- $\Psi'' = \frac{2m\,(V-E)}{\hbar^2}\Psi$ — (1) Schrodinger Equation
- $\Psi = e^{-\phi(x)}$ — (2) Assume form of Ψ
- $-\phi''(x) + \phi'(x)^2 = \frac{2m\,(V-E)}{\hbar^2}$ — (3) $\phi''(x) = 0$ (slowly varies)
- $\phi(x) \approx \int_{x_0}^{x} \sqrt{\frac{2m\,(V-E)}{\hbar^2}}\,\mathrm{dx}'$ — (4) WKB (w/ eq. (2))
- $V(r) = \frac{e^2}{4\,\pi\epsilon_0 r}, E = \frac{e^2}{4\,\pi\epsilon_0 r_{tp}}$ — (5) For 1D Z=1 Barrier
- $\phi(r_{tp}) \sim \sqrt{r_{tp}} \sim {}^{1}/_{\sqrt{E}}$ — (6) Apply eq. (4) to eq. (5)
- $\Psi(r_{tp}) \sim e^{{}^{1}/_{\sqrt{E}}}$ — (7) Apply eq. (2) to eq. (6)

Simplified Scaling Estimate

$$V_H = \frac{4}{3}\pi R_H^3 \qquad V_C = 4\pi R_H^2 \Delta R$$



1. Energy Balance (Assume $p_H = p_S$)

$$\frac{3}{2}pV_H + \frac{3}{2}pV_S = \frac{1}{2}M_C v_{imp}^2$$

$$p = \rho \frac{\Delta R}{R_H} v_{imp}^2$$

2. Partially Fermi Degenerate Shell

$$p \propto \alpha\, \rho_C^{5/3}$$

$$\rho_C \propto \left(\frac{\Delta R}{R_H}\right)^{3/2} \frac{1}{\alpha^{3/2}} v_{imp}^3$$

$$\frac{p}{p_D} \equiv \alpha, \quad p_D \equiv \frac{(3\pi^2)^{\frac{2}{3}}\hbar^2}{5m_e}(\rho)^{5/3}$$

3. Areal Density

$$\rho_C R_H \sim \frac{v_{imp}^3}{\alpha^{3/2}} S$$

$$M_C \sim R_0^3 \sim S^3$$

4. Yield

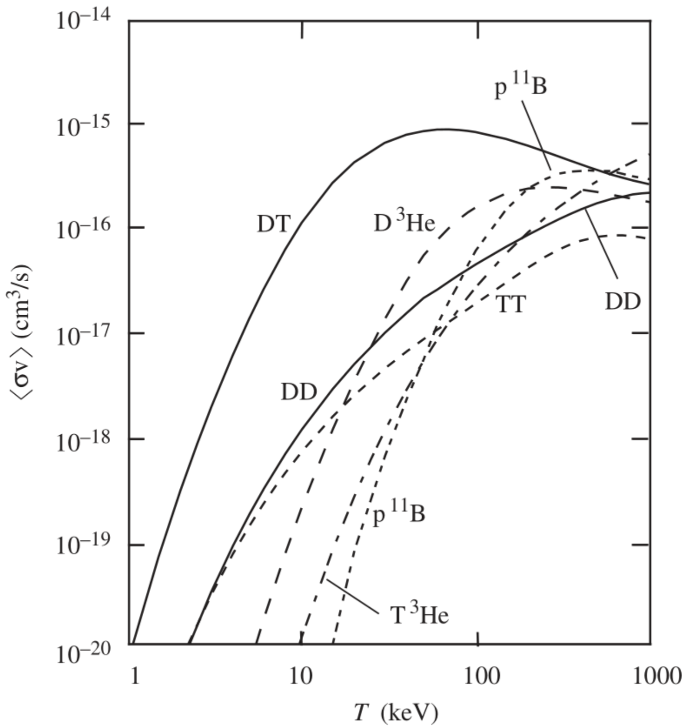
$$Y \sim \Phi M_C \sim \rho_C R_H M_C \sim \frac{v_{imp}^3}{\alpha^{1.5}} S^4$$

Compare to

$$Y \sim P_{abl}^{0.64} \frac{v_{imp}^{4.47}}{\alpha^{1.44}} S^{4.67}$$

Reactivity

$$\langle \sigma v \rangle_{DT} = \begin{cases} 4.2 \times 10^{-20} (T_{keV})^4 cm^3 s^{-1} & \text{if } 3 < T_{keV} < 6 \\ 1.1 \times 10^{-18} (T_{keV})^2 cm^3 s^{-1} & \text{if } 8 < T_{keV} < 25 \end{cases}$$



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$$\langle \sigma v \rangle = \frac{4\pi}{(2\pi m_r)^{1/2}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty \sigma(\epsilon)\, \epsilon \, \exp(-\epsilon / k_B T) d\epsilon.$$