Multistage Fusion Reaction Rates in an Adiabatically Compressed Plasma

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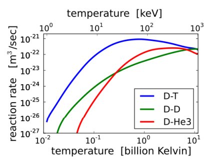
What is Nuclear Fusion?

Energy is released when light nuclei fuse to form heavier nuclei. This is the energy which powers stars such as the Sun. The amount of energy released is related to the difference in the masses of the initial and final nuclei according to $E = mc^2$.

Nuclear forces are of short range. Hence reactions occur only when nuclei are in close proximity and to achieve this they must have energy sufficient to overcome their repulsive electrostatic forces. This requires such high temperatures as 15,000,000 K as in the Sun.

Challenges and objectives

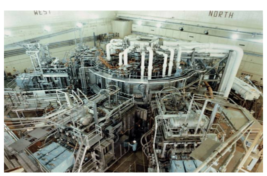
- Achieve temperatures such as that in the Sun's interior;
- Confine reacting species long enough for fusion reactions to occur;
- Achieve energy break-even: output energy compensates input energy.



Two Major Approaches to Fusion

Magnetic confinement. A low density plasma of H^+ ions is confined by magnetic fields.

Inertial confinement. A pellet of solid H is bombarded by high-intensity lasers.



Primary reactions:

D + D → T + p + 4.03 MeV; D + D → ^{3}He + n + 3.27 MeV

$<\sigma v> \approx 10^{-14}\, T^{-2/3} \exp(-19T^{-1/3})$ cm³ / s for T < 50 keV

Secondary reactions

D + T → α + n + 17.6 MeV; D + ^{3}He → α + p + 18.3 MeV

Fusion reaction rates proportional to n^2.

n = particle density.

Magnetic confinement methods: ≈ 10^{15} cm³ ⇒ requires T ≈ 10^8 K

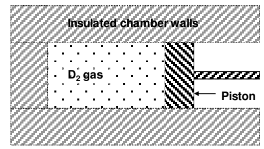
Proposed Method

Exploit n^2 factor under reduced degrees of freedom

Perform under adiabatic conditions

⇒ appreciable fusion rates at lower T

Mechanical adiabatic compression



Dense gas of D_2 undergoes adiabatic compression

Rapid process - - explosively driven

Well-insulated chamber – retain energy internally

Starting conditions.

One mole D_2 at atmospheric pressure and room temperature.

Apply compression. Compression factor $\beta = V_0 / V$. T increases.

D_2 molecules → D_2 atoms → D_2 atoms ionize

→ deuteron-electron plasma → Fusion of deuterons.

Assumptions:

Reversible adiabatic compression

Apply equilibrium thermodynamics

Treat as *van der Waals* (vdW) gas: $(P + aN^2/V^2)(V - Nb) = RT$

Degrees of freedom

γ = specific heat ratio

Related to number of degrees of freedom f of the gas: $\gamma = (f + 2) / f$

For monoatomic gas: f = 3

Deprive particles of freedom of motion ⇒ larger T increase for given energy input. Accomplish with

(1) External magnetic field(s)

(2) Electric discharge in direction of piston motion.

Also ⇒ Pinch Effect.

Adiabatic compression of a vdW gas

$$T = T_0 \left(\frac{V_0 - Nb}{V - Nb}\right)^{\gamma - 1} = T_0 \left(\frac{\beta(V_0 - Nb)}{V - \beta Nb}\right)^{2/f}$$

Work to compress a van der Waals gas

$$W = -\int_{V_0}^{V} P\,dV = \frac{NRT_0 f}{2}\left[\left(\frac{\beta(V_0 - Nb)}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1$$

Energy release

Reaction rate: $r = \frac{1}{2} n^2 <\sigma v>$

σ = reaction cross section; v = relative velocity of interacting nuclei

Energy release in time Δt: $\Delta E = r\, Q\, V\, \Delta t$. V = final volume

Q = avg energy release/reaction. Previously considered fusion to occur only at end of compression. Present work computes T and ΔE at various stages of the compression.

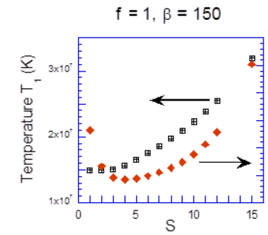
Multistage data for vdW gas

Consider only D+D: Avg Q = 3.65 MeV

Calculate final T and ΔE / *W* as function of total no. of stages S.

Total Δt = 0.001 sec.

T and ΔE / *W* vary directly with S.

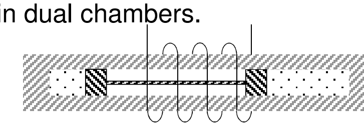


Applications

Single shot: Neutron source to initiate fission.

Multiple compressions in dual chambers.

Dual pistons with coil to extract work



Summary and conclusions

Exploited n^2 factor and reduced degrees of freedom.

Adiabatic conditions ⇒ energy retained internally.

Found some favorable cases.

To be more realistic:

- Not all input energy serves to compress gas.
- Consider particle losses via leakage.

Compensated by ignoring:

- D-T reactions; Pinch Effect.
- Enhancements: Deuterated walls; Screening effects of electrons.