Lecture #25 The Holy Grail of Plasma Physics: Controlled Thermonuclear Fusion — Howes ①

I. Nuclear Fusion: The Energy Source of the Stars

A. The CNO Cycle

1. In 1938/1939, Carl von Weizsäcker & Hans Bethe independently proposed this chain of nuclear reactions as the source for stellar luminosity
2. $^{12}_{6}C$ acts as a catalyst to fuse four protons into an alpha particle
   a. Mass Number $A=12$ → $^{12}_{6}C$ ← Element; Atomic Number $Z=6$

   $^{1}_{1}H = p$ $\quad$ $^{4}_{2}He = \alpha$

   $^{2}_{1}H = D$ $\quad$ $^{1}_{0}n$

   $^{3}_{1}H = T$ $\quad$ $^{0}_{-1}e$ $\quad$ $^{0}_{+1}e^{+}$

   b. Thus, the net reaction is

$$^{12}_{6}C + 4\,^{1}_{1}H \longrightarrow \,^{12}_{6}C + \,^{4}_{2}He + 2\,^{0}_{1}e^{+} + 2\nu_e + 3\gamma$$

   (e^{+}: positron; ν_e: electron neutrino; γ: gamma ray)

   (6 reactions)

3. This is the dominant power source for stars with $M > 1.5 M_\odot$
   a. CNO reactions occur for $T > 1.3\times10^{7}K$
   b. Our Sun has a central temperature $T \simeq 1.57\times10^{6}K$
      $\Rightarrow$ only 1.7% of α's are produced by CNO in Sun.

   c. At $T > 1.7\times10^{7}K$ CNO begins to dominate.

B. The p-p cycle

1. $p + p \rightarrow D + e^{+} + \nu_e$ (1.44 MeV)

   $D + p \rightarrow \,^{3}_{2}He + \gamma$ (5.49 MeV)

   $^{3}_{2}He + \,^{3}_{2}He \rightarrow \,^{4}_{2}He + 2p$ (12.86 MeV)

I B. Continued)

2. The lower central temperatures in the sun lead to dominance of the p-p cycle.
3. p-p cycle requires $T > 4\times10^6$ K.

C. Laboratory Fusion: D-T reaction

1. Basic characteristics for fusion in the lab:

$$D + T \longrightarrow {}^4_2He + {}^1_0n \qquad 17.6\text{ MeV}$$

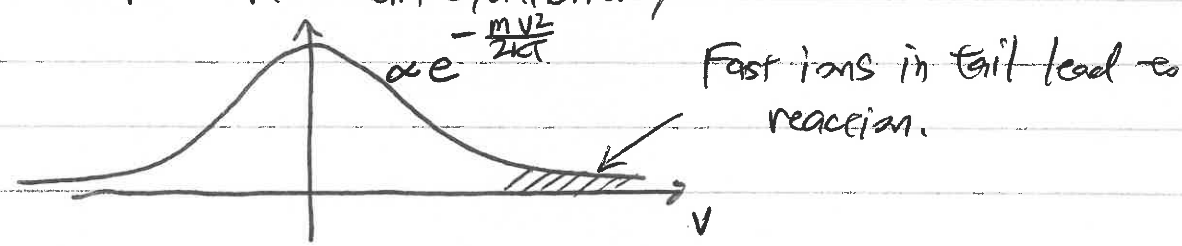
He: (3.5 MeV) (20% of energy); n: (14.1 MeV)

Need to achieve $T \sim 10$ keV

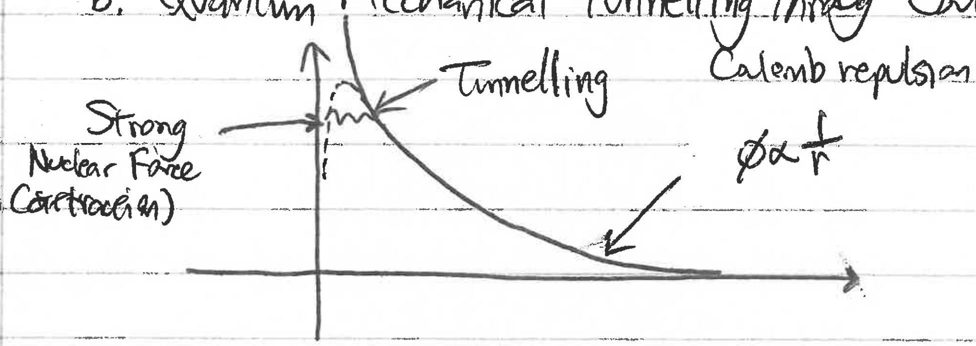
2. Reactions relevant to Laboratory Fusion ⇒ p.44-45 NRL Plasma Formulary.

3. D-T reaction cross-section peaks at ~50 keV, but you don't need a plasma with $T \sim 50\text{ keV} \sim 6\times10^8$ K.

a. For a Maxwellian equilibrium,



b. Quantum Mechanical Tunnelling through Coulomb Barrier.



4. Difficulties
   a. Confinement
   b. Fast neutrons
   c. Tritium supply.

I. C. (Continued)

5. **Neutrons:** 14.1 MeV neutrons are not contained
   ⇒ Can cause severe damage and weakening of reactor material.

6. **Tritium:**
   a. Cost for tritium is estimated at $84,000 to $130,000/gram.
   b. Need a way to produce tritium
      ⇒ Breeder Reactions: Lithium Blanket
      $$n + {}^{6}_{3}Li \longrightarrow {}^{4}_{2}He + T$$
   c. Can use neutrons from D-T reaction to produce more T.
   d. World's supply of Lithium is limited, but sufficient to supply world's energy demands for thousands of years.

D. The Lawson Criterion:

1. Balance power lost by plasma with power released by fusion reaction.
2. Fusion power in α's:
   a. $n_D = n_T = n$
   b. $P_\alpha = \frac{1}{4} \langle \sigma v \rangle n^2 E_\alpha$ $\qquad E_\alpha = 3.5$ MeV

      $\langle \sigma v \rangle$: cross-section × velocity averaged over a Maxwellian distribution
   c. Efficiency for retaining α power in plasma: η
3. Power Loss: a. Loss of confinement $P_c = \frac{-3nkT}{\tau}$

      τ = confinement time

   b. Radiative losses (for example, Bremsstrahlung from electron-ion collisions)
      $P_B = -\alpha n^2 T^{\frac{1}{2}}$ $\quad \alpha$ = const.

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I. D. (Continued)

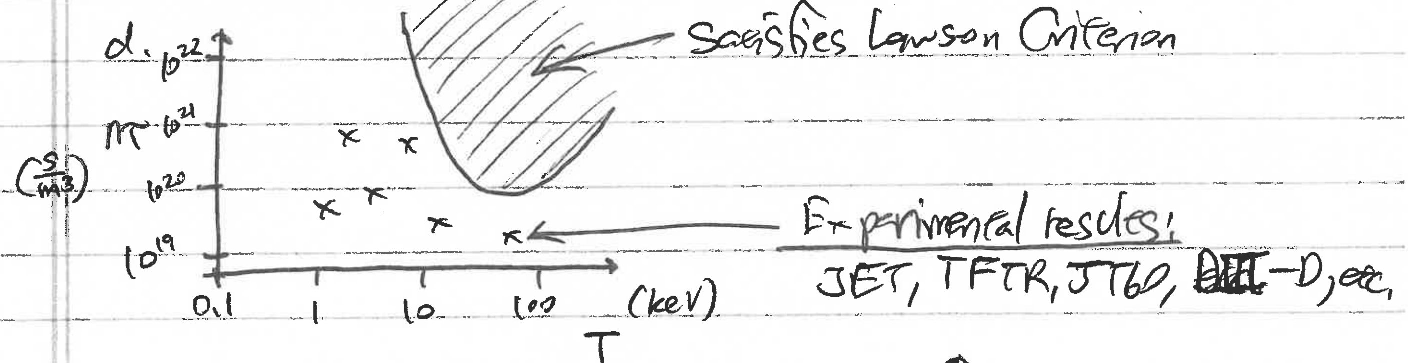
4. Power Balance: $P_\alpha + P_B + P_C > 0$ to sustain fusion

a. $\frac{n}{4}\langle\sigma v\rangle n^2 E_\alpha - \alpha n^2 T^{\frac{1}{2}} - \frac{3nkT}{\tau} > 0$

b. $\frac{n}{4}\langle\sigma v\rangle E_\alpha - \alpha T^{\frac{1}{2}} > \frac{3nkT}{n^2\tau}$

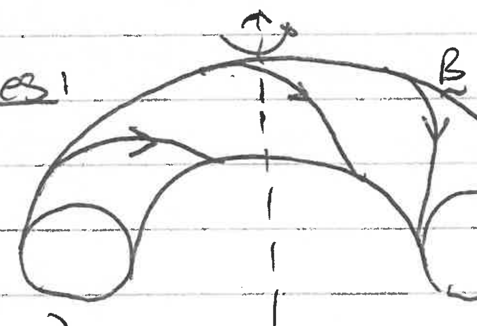
c. $n\tau > \frac{3kT}{\frac{n}{4}\langle\sigma v\rangle E_\alpha - \alpha T^{\frac{1}{2}}}$ Lawson Criterion

d.



II. Plasma Confinement Schemes:

A. Magnetic Confinement:



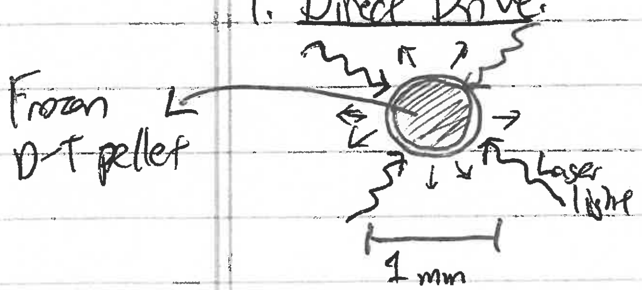
1. Tokamak: Most successful.
(Russian: Toroidal Magnetic Chamber)

2. Other: Z-pinches, Reverse Field Pinches, Stellarator, etc.

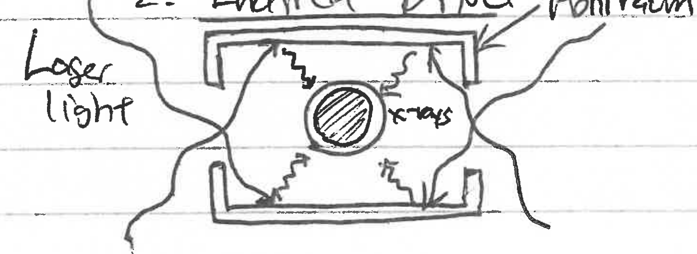
3. Requires plasma confinement times of at least a few seconds.

B. Inertial Confinement (Laser Fusion)

1. Direct Drive:



2. Indirect Drive:



3. Both reaction compresses plasma to 10^3 times liquid density for very short times.