LECT 22. NUCLEAR FUSION

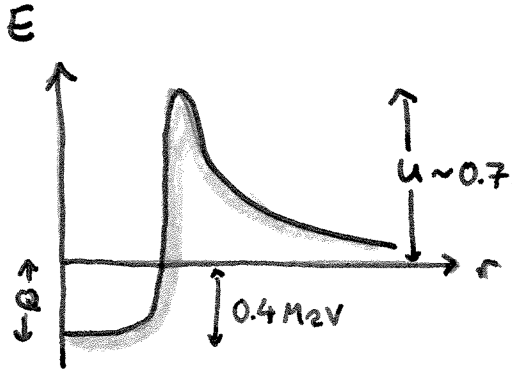
The frightening power of a hydrogen bomb, the sunshine that comes from the sun — both are examples of a source of power — fusion power — that mankind has yet to successfully tame for peaceful uses.

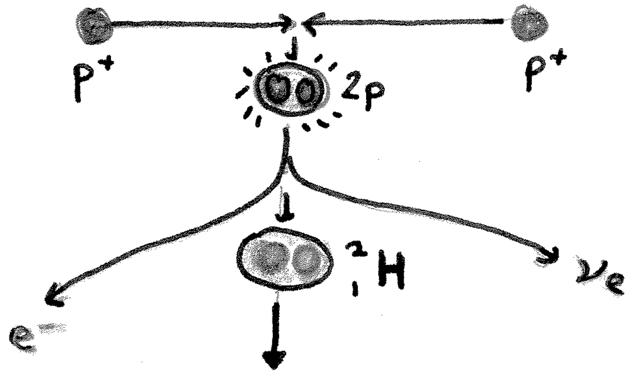
Nuclear fission takes advantage of the energy gained by splitting large heavy nucleii into smaller, more stable components. By contrast, fusion takes advantage of the additional stability obtained by combining lighter nucleii. Iron and nickel have the largest binding energies per nucleon and are therefore the most stable.

It follows that the fusion of nucleii lighter than iron or nickel generally releases energy.

It takes considerable energy to bring nucleii together for fusion, basically because of the huge Coulomb forces that repel like charged nucleii. Nevertheless, the energy released once the nuclei fuse is far greater.

FUSION OF TWO PROTONS





$$\text{Coulomb Energy barrier} = U = \frac{e^2}{4\pi\varepsilon_0 r} = \frac{(1.6\times10^{-19}\,C)^2\times(9\times10^{9}\,Jm/C^2)}{2\times10^{-15}\,m}$$

$$\simeq 1.2\times10^{-13}\,J$$

$$= \underline{\underline{0.7\ MeV}}$$

$$Q = (2m_p - m_D - m_e)c^2$$

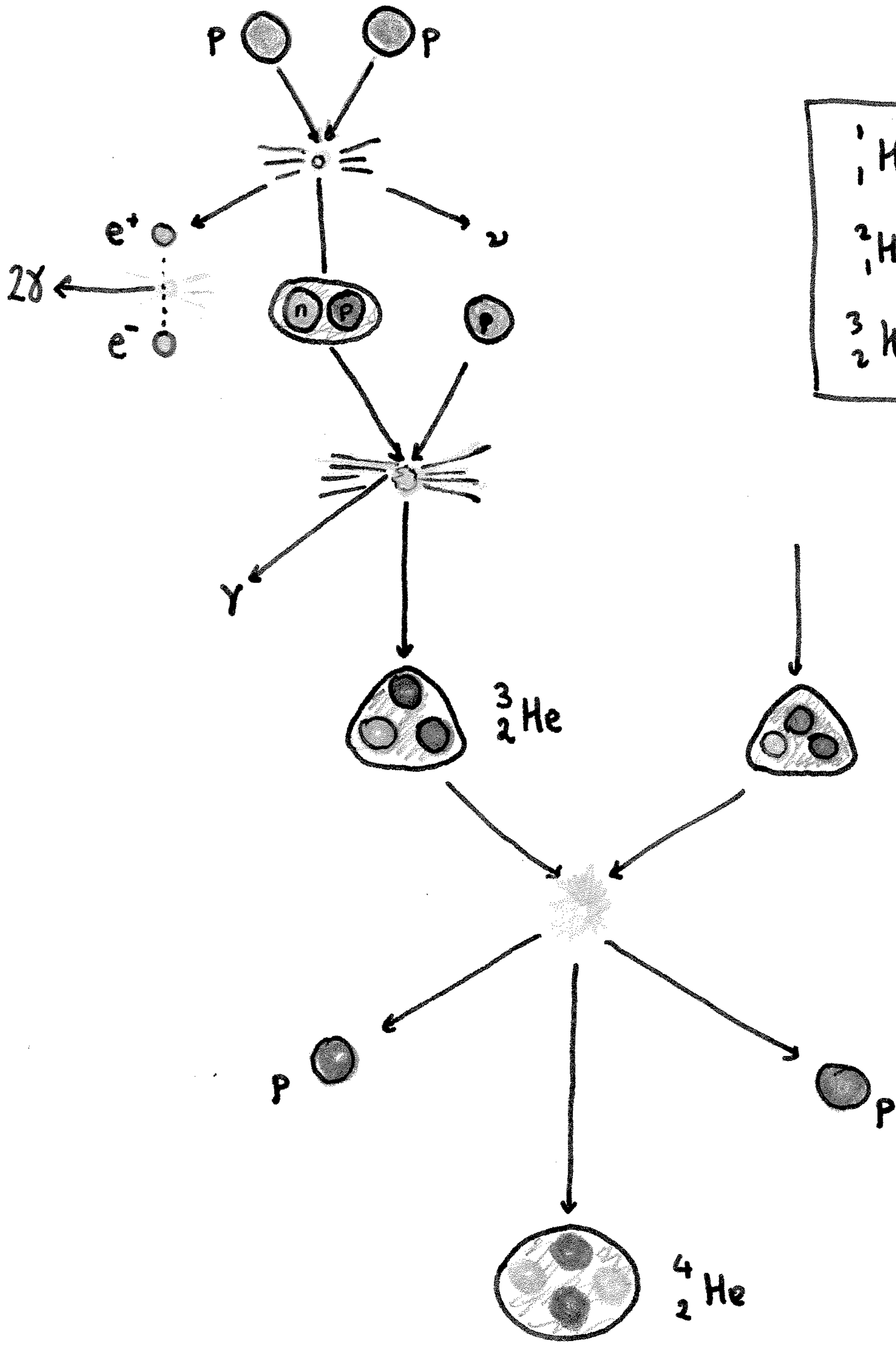
$$= \left[2({}^1_1M) - {}^2_1M - 2m_e\right]c^2$$

$$= \left[2(1.007825) - 2.014102 - 2(0.000548)\right]\times 931.5\ MeV/u$$

$$= \underline{0.421\ MeV}$$

$$\boxed{\text{THIS IS THE FIRST AND KEY STEP IN SOLAR FUSION.}}$$

PROTON-PROTON CHAIN



$${}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu_e$$

$${}^2_1H + {}^1_1H \longrightarrow {}^3_2H + \gamma$$

$${}^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H$$

Dominates Stars the size of the sun or smaller.

$4\ m_p$	$4.02911\ u$	$= ({}^1_1M - m_e) \times 4$
Mass ${}^4He$	$4.002603\ u$	$= ({}^4_2M - 2m_e)$
Mass diff	$0.026503\ u$	$\equiv \underline{24.69\ MeV}$

$$e^+ + e^- \longrightarrow 2\gamma$$

$$Q = 2(0.511) = 1.022\ MeV$$

$$\boxed{\text{Total energy} / 4p = 24.69 + 2.044 = \underline{26.73\ MeV}}$$

$\#$ protons / g of sun $\sim 4.5 \times 10^{23}$

$$\text{Energy}/g \approx \frac{26.73}{4} \times 4.5 \times 10^{23} = 3 \times 10^{24}\ MeV$$

$$\equiv 5 \times 10^{11}\ J$$

$$\simeq \underline{130\ kWHr/g}.$$

SUN: Enough protons to last 75 BILLION YRS.

Controlled Fusion

H-fusion . How hot must a gas be for fusion?

$$\frac{3}{2} k_B T = E$$

$$T = \frac{2E}{3k_B} \approx \frac{2\,(0.6 \times 10^{-13}\,\text{J})}{3\,(1.4 \times 10^{-23}\,\text{J/K})} = 3 \times 10^{9}\,\text{K}$$

The core of the sun has $T \sim 1.5 \times 10^{7}$ K, and only the electrons at the edge of the Maxwell-Boltzmann distribution achieve fusion. The energy release rate in the core of the sun is about

$$0.1\ \mu\text{W/cm}^3 \qquad !$$

No use for terrestrial devices - we have to do for better!

In a practical fusion reactor require temperatures $\sim 10^{8}$ K. for "breakeven" e.g A Deuteron & a Tritium nucleus fuse to form an alpha particle and a neutron. How much energy is liberated?

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$$

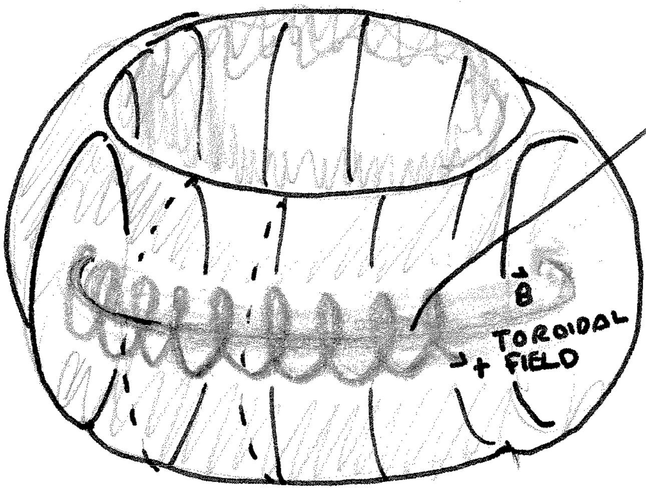
$^{2}_{1}H$	2.014102u	$^{4}_{2}He$	4.002603
$^{3}_{1}H$	3.016049u	$^{1}_{0}n$	1.008665

$M_{initial} = \underline{5.03015}$ $\qquad$ $M_{Final} = \underline{5.01127}$

$$(M_i - M_f) \times 931.5 = \underline{\underline{17.59 \text{ MeV}}}$$

The detection of α-particles in a Tokamak is an important indication that fusion is taking place.

MAGNETIC CONFINEMENT: THE TOKAMAK



PLASMA ~ 100MK

Contains fuel:-

Deuterium	${}^2_1H$
Tritium	${}^3_1H$

TOKAMAK

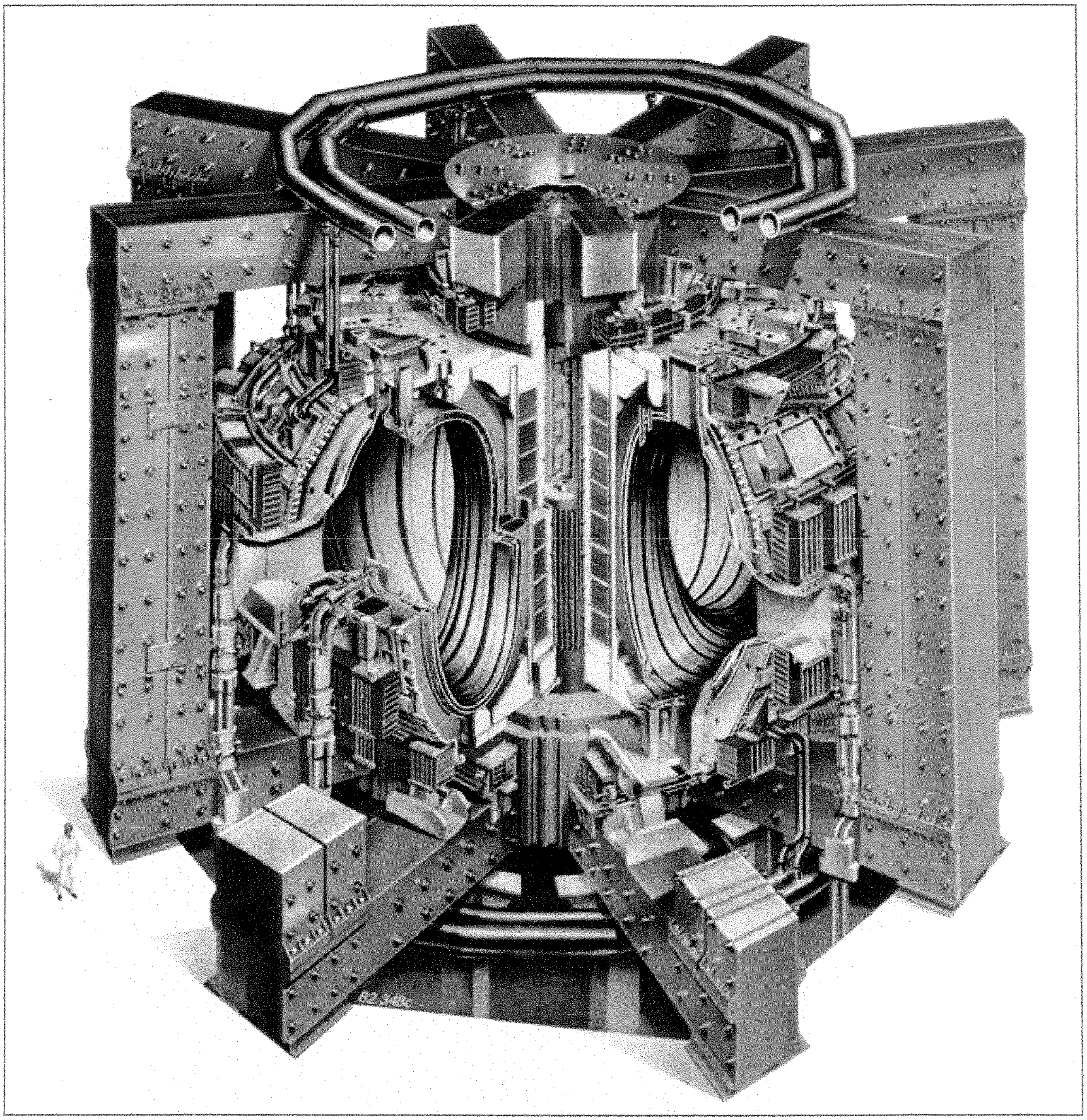
see www.jet.efda.org

	Q/MeV
$D + D \rightarrow T + H$	4
$T + D \rightarrow {}^4He + n$	17.6
$D + D \rightarrow {}^3He + n$	3.3
${}^3He + D \rightarrow {}^4He$	18.3

TFTR (Princeton, NJ) 10.7MW (1994) (1982-1997)

JET (Cullham, UK) 70% of power required to heat PLASMA.

ITER (Cadarache, France 2015) 500MW Fusion Power $\boxed{\text{IGNITION}}$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Other less successful ideas

- INERTIAL CONFINEMENT. (Lasers compress & heat fuel pellets)
- MUON CATALYZED FUSION $\,{}^1_1H \cdots \mu^- \cdots {}^1_1H$ TINY MOLECULE → COLD FUSION !