Breeding deuterium and the ultimate fusion fuel cycle

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FuseNet PhD Event
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	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li	^{7}Li	^{9}Be
^{1}H	Nope							
^{2}H	Nope	Very Hard						
^{3}H	Nope	Hard	Very Hard					
^{3}He	Nope	Very Hard	Almost Impossible	Nope				
^{4}He	Nope	Nope	Nope	Nope	Nope			
^{6}Li	Almost Impossible	Almost Impossible	Almost Impossible	Nope	Nope	Nope		
^{7}Li	Nope	Almost Impossible	Almost Impossible	Nope	Nope	Nope	Nope	
^{9}Be	Almost Impossible	Almost Impossible	Almost Impossible	Nope	Nope	Nope	Nope	Nope
^{10}B	Nope	Nope	Nope	Nope	Nope	Nope	Nope	Nope

@JB_Fusion

Outline

J. Ball. *Nuclear Fusion* **59** 106043 (2019).

- Review fusion fuel cycles
- Present the catalyzed D-D+D fuel cycle
- Explain how it can be accomplished
- Discuss why we might care someday :)

Fusion fuel cycles

[1] Rider. *MIT PhD.* (1995).

D-T:

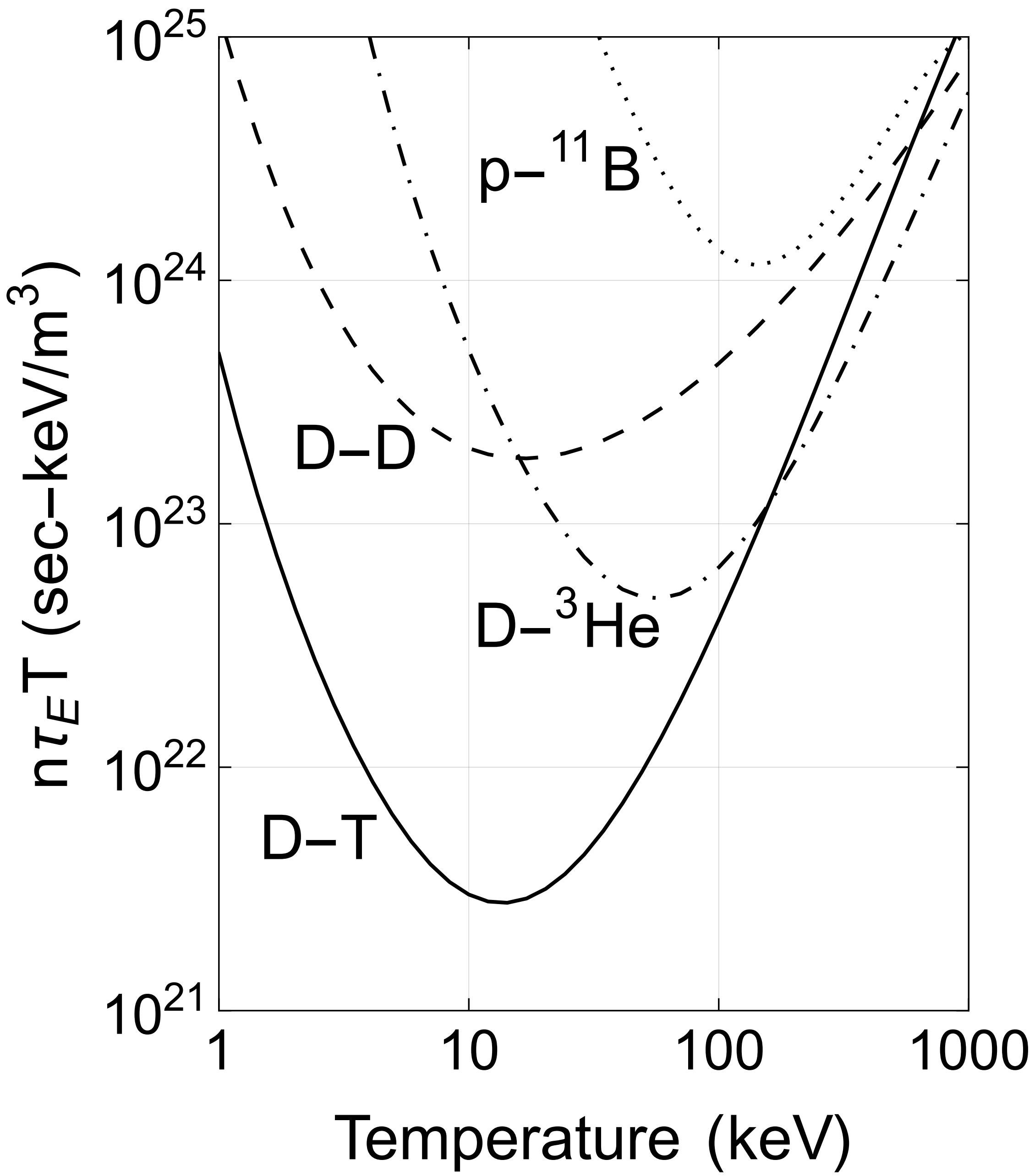
D + T → ^{4}He + n + 17.6MeV

D-^{3}He:

D + ^{3}He → ^{4}He + H + 18.4MeV

D-D:

$$\mathbf{D + D} \begin{array}{l} \nearrow \mathbf{T + H + 4.0MeV} \\ \searrow \mathbf{{}^3He + n + 3.3MeV} \end{array}$$



Fusion fuel cycles

[1] Rider. *MIT PhD.* (1995).

D-T: radioactive

D + T → ^{4}He + n + 17.6MeV

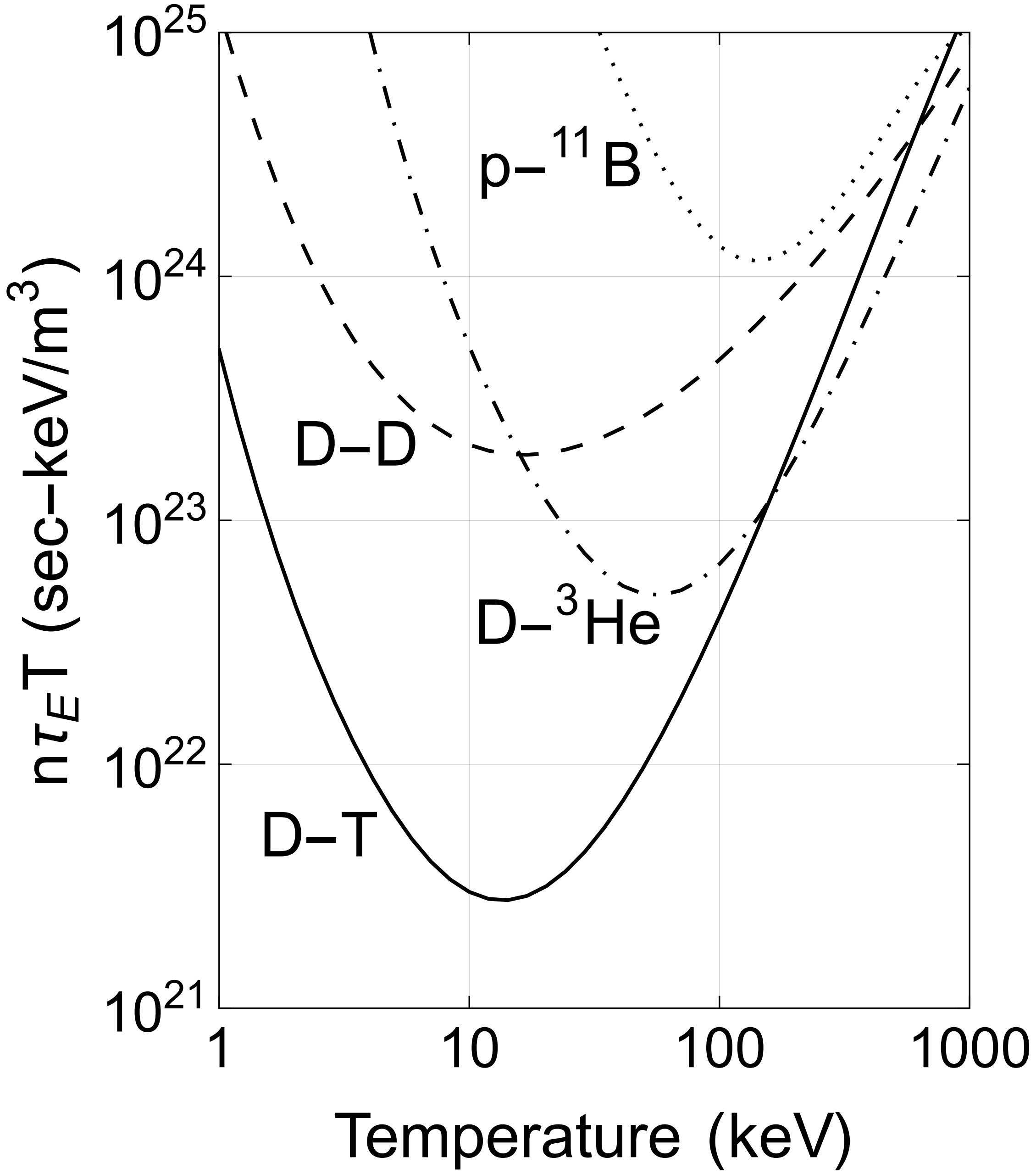
D-^{3}He:

D + ^{3}He → ^{4}He + H + 18.4MeV

atmospheric escape

D-D:

4 D → ^{3}He + T + H + n + 7.3MeV



- Only three fusion reactions appear feasible due to bremsstrahlung[1]

Fusion fuel cycles

[1] Rider. *MIT PhD.* (1995).

D-T:

$$D + \cancel{T} \rightarrow {}^4He + \cancel{n} + 17.6\text{MeV}$$

$${}^6Li + \cancel{n} \rightarrow {}^4He + \cancel{T} + 4.8\text{MeV}$$

$$D + {}^6Li \rightarrow 2\ {}^4He + 22.4\text{MeV}$$

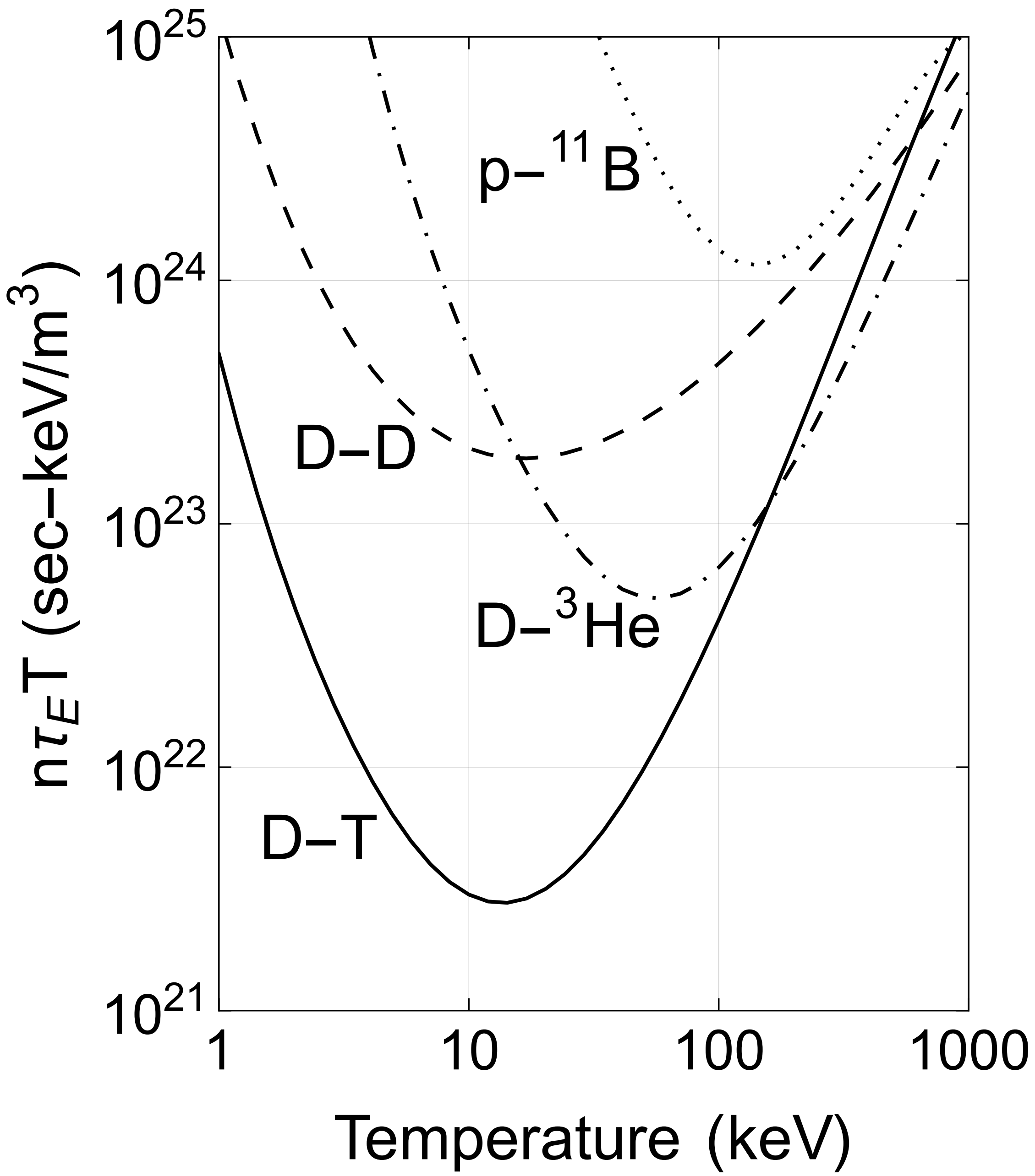
D-^{3}He:

$$D + {}^3He \rightarrow {}^4He + H + 18.4\text{MeV}$$

moon?

D-D:

$$4\ D \rightarrow {}^3He + T + H + n + 7.3\text{MeV}$$



- Only three fusion reactions appear feasible due to bremsstrahlung[1]

Fusion fuel cycles

Catalyzed D-D:

$$\begin{array}{l}
4\ \mathrm{D} \rightarrow \cancel{{}^{3}\mathrm{He}} + \cancel{\mathrm{T}} + \mathrm{H} + \mathrm{n} + 7.3\mathrm{MeV} \\
\mathrm{D} + \cancel{\mathrm{T}} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\mathrm{MeV} \\
\mathrm{D} + \cancel{{}^{3}\mathrm{He}} \rightarrow {}^{4}\mathrm{He} + \mathrm{H} + 18.4\mathrm{MeV} \\
\hline
6\ \mathrm{D} \rightarrow 2\ {}^{4}\mathrm{He} + 2\ \mathrm{H} + 2\ \mathrm{n} + 43.2\mathrm{MeV}
\end{array}$$

Catalyzed D-D+D:

$$\begin{array}{l}
\overset{4}{\cancel{6}}\ \mathrm{D} \rightarrow 2\ {}^{4}\mathrm{He} + \cancel{2\ \mathrm{H}} + \cancel{2\ \mathrm{n}} + 43.2\mathrm{MeV} \\
\cancel{2\ \mathrm{H}} + \cancel{2\ \mathrm{n}} \rightarrow \cancel{2\ \mathrm{D}} + 4.4\mathrm{MeV} \\
\hline
4\ \mathrm{D} \rightarrow 2\ {}^{4}\mathrm{He} + 47.6\mathrm{MeV}
\end{array}$$

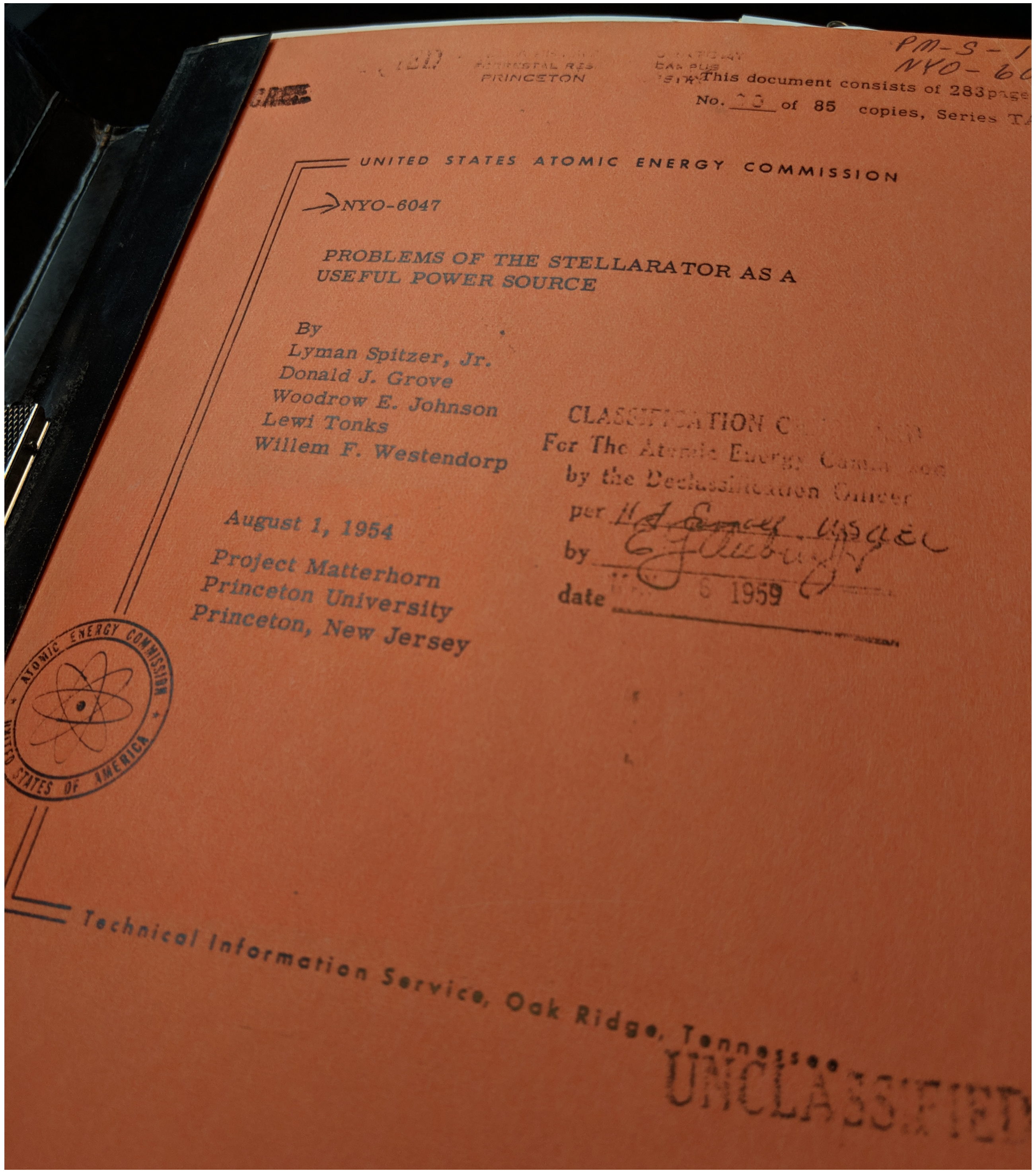
thermal cross-section
of ~0.3 barns

$$\Rightarrow \boxed{2\ \mathrm{D} \rightarrow {}^{4}\mathrm{He} + 23.8\mathrm{MeV}}$$

- Seems fairly obvious, but has never been pointed out before

ASIDE: Spitzer’s perspective from 1954

- Stellarator burning D-T with a lithium breeding blanket
- Included divertors to prevent cool atoms from being sputtered into the plasma
- “Evidently the stellarator tends to be a large device.”
    - 5 GW, a major radius of 3 meters, copper coils, 7.5 Tesla
- Noted the importance of high magnetic field



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UNITED STATES ATOMIC ENERGY COMMISSION

NYO-6047

PROBLEMS OF THE STELLARATOR AS A USEFUL POWER SOURCE

By
Lyman Spitzer, Jr.
Donald J. Grove
Woodrow E. Johnson
Lewi Tonks
Willem F. Westendorp

August 1, 1954

Project Matterhorn
Princeton University
Princeton, New Jersey

CLASSIFICATION C
For The Atomic Energy Commission
by the Declassification Officer
per H. J. USAEC
by
date 6 1959

Technical Information Service, Oak Ridge, Tennessee

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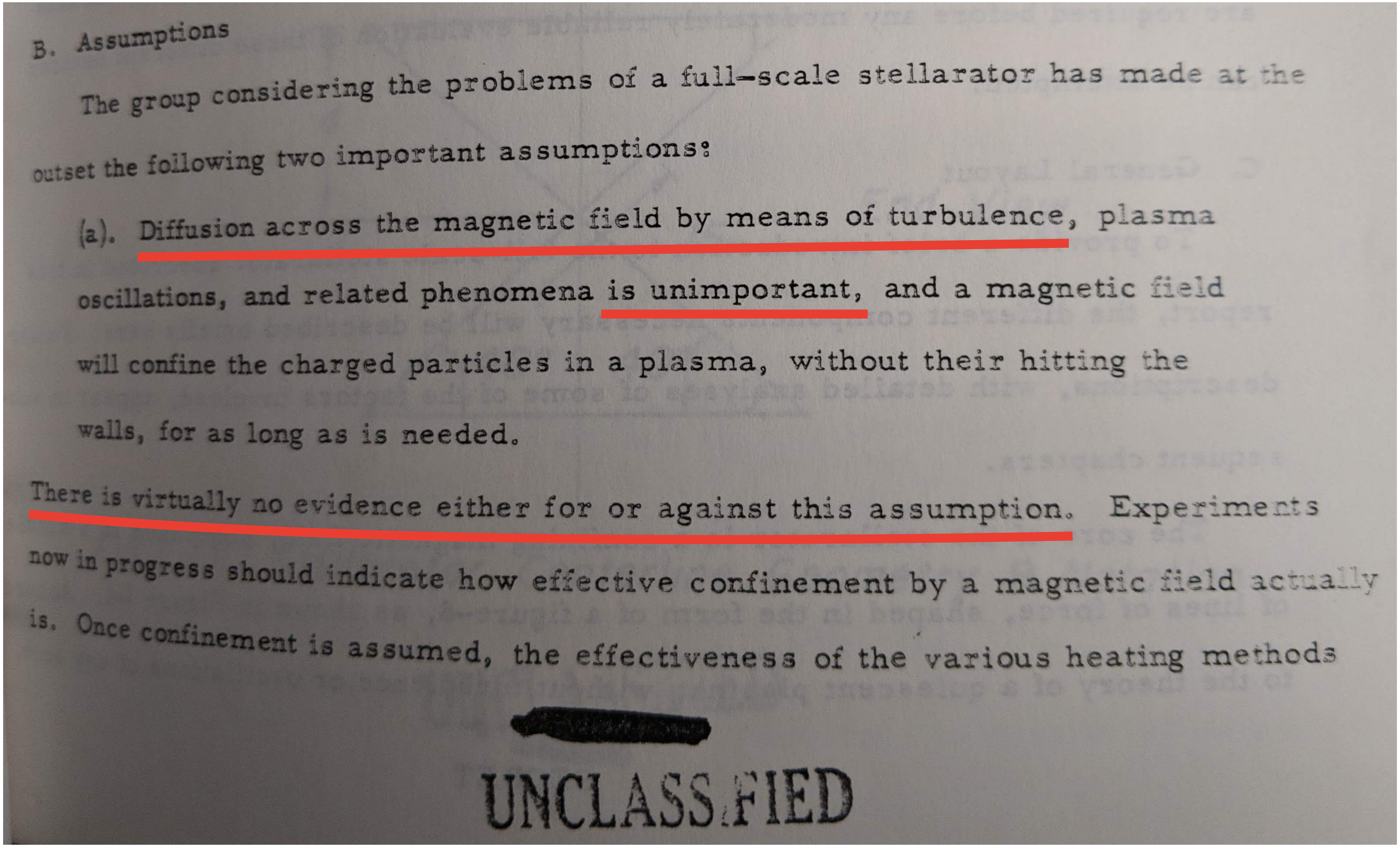
ASIDE: Spitzer’s perspective from 1954



B. Assumptions

The group considering the problems of a full-scale stellarator has made at the outset the following two important assumptions:

(a). Diffusion across the magnetic field by means of turbulence, plasma oscillations, and related phenomena is unimportant, and a magnetic field will confine the charged particles in a plasma, without their hitting the walls, for as long as is needed.

There is virtually no evidence either for or against this assumption. Experiments now in progress should indicate how effective confinement by a magnetic field actually is. Once confinement is assumed, the effectiveness of the various heating methods

[redacted]

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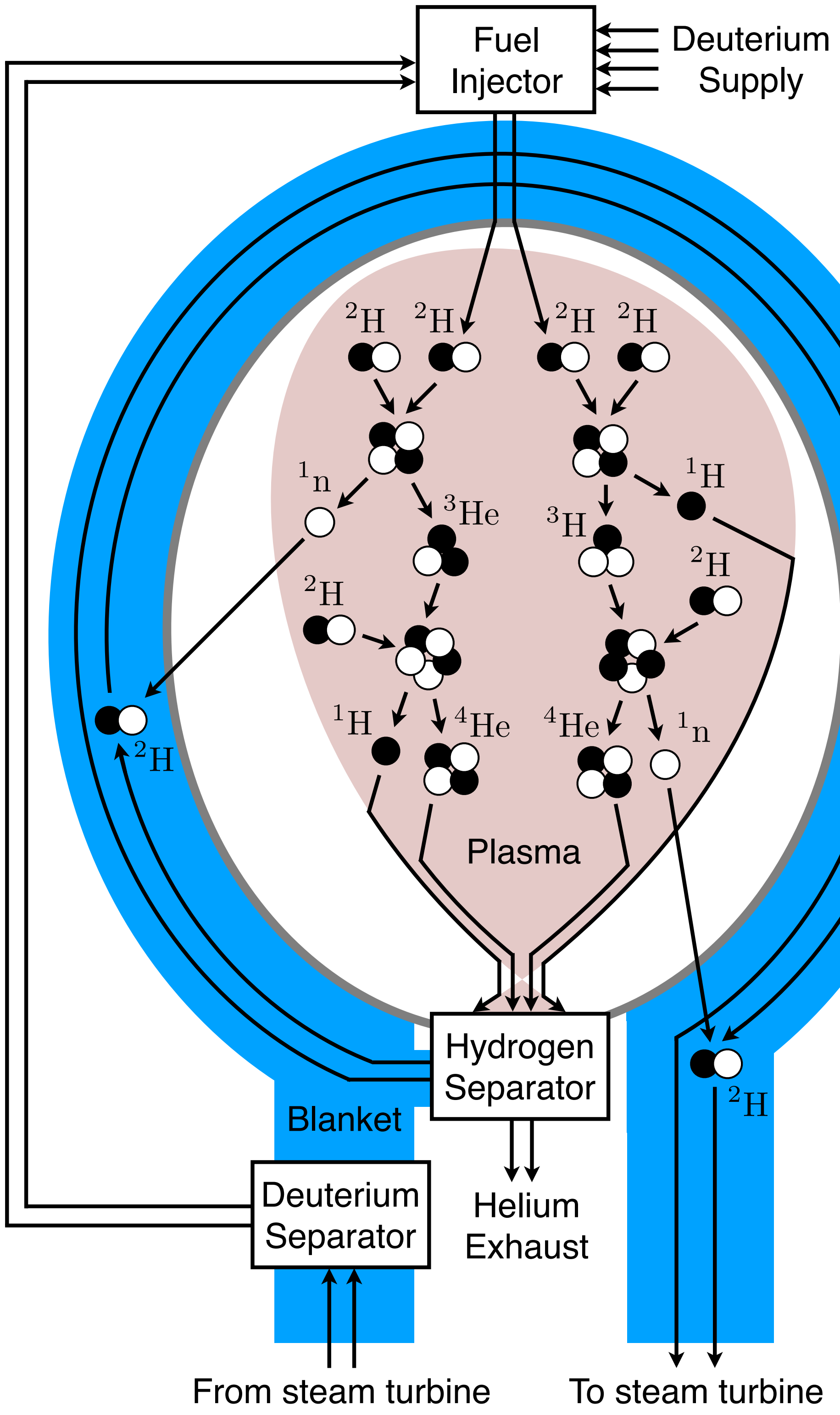
How to achieve the catalyzed D-D+D fuel cycle?

$$\mathbf{2\ D \rightarrow {}^{4}He + 23.8MeV}$$

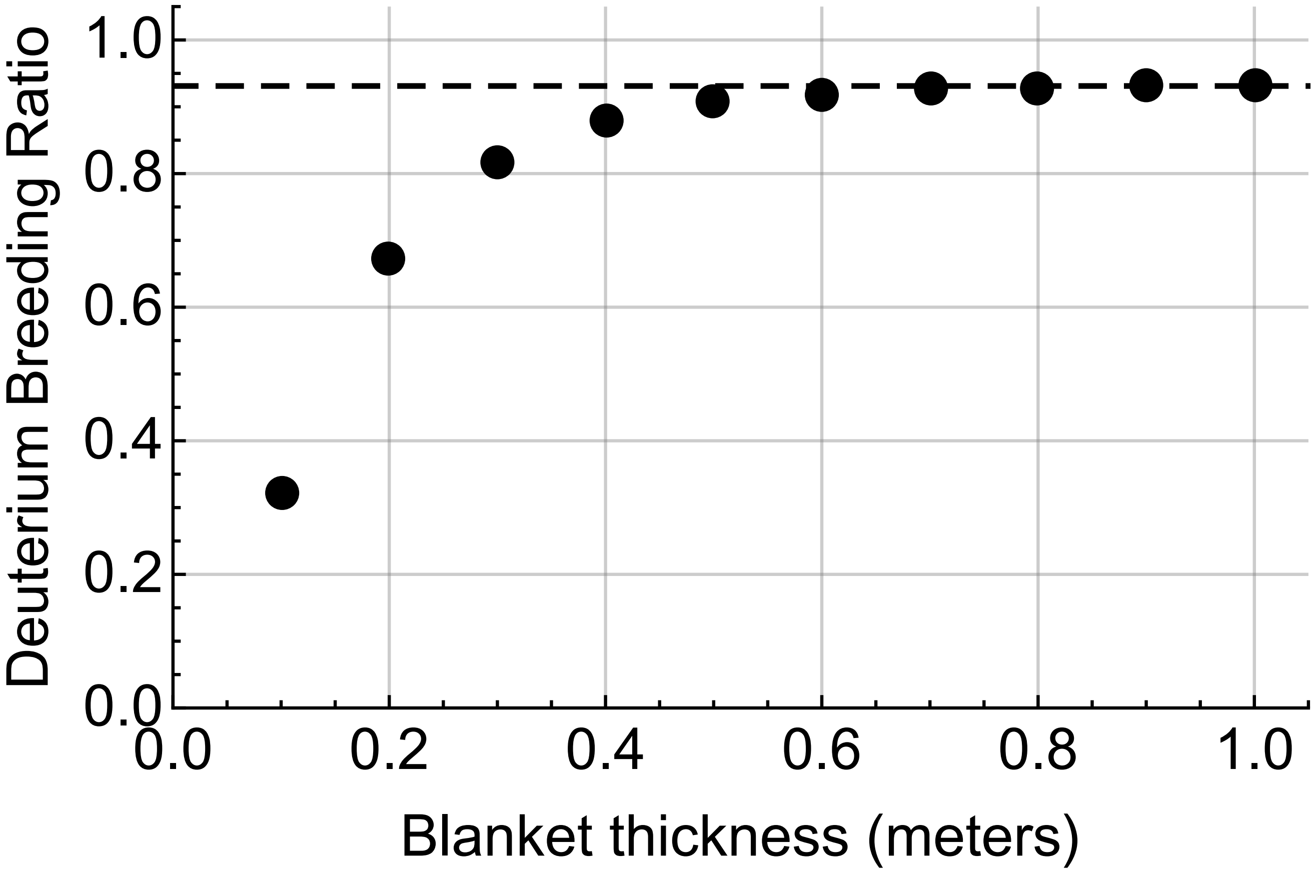
- Put the reactor in a tank of water
- In a water-cooled D-D device this would happen inadvertently



How to achieve the catalyzed D-D+D fuel cycle?

$$2\ D \rightarrow {}^{4}He + 23.8MeV$$

- Put the reactor in a tank of water
- In a water-cooled D-D device this would happen inadvertently
- Blanket thickness is similar to a *tritium* breeding blanket



- No need for neutron multiplication: falling somewhat short of DBR=1 just means you need somewhat more deuterium as input

Why do we care? More energy

[1] Tytler, *et al. Physica Scripta* (2000).

- Breeding deuterium enables any given supply of deuterium to produce as much as 65% more energy:

$$3\ \mathrm{D} \rightarrow {}^{4}\mathrm{He} + \mathrm{H} + \mathrm{n} + 21.6\,\mathrm{MeV}$$

$$\Downarrow$$

$$2\ \mathrm{D} \rightarrow {}^{4}\mathrm{He} + 23.8\,\mathrm{MeV}$$

- Deuterium is the dominant fuel source on Earth and in the universe

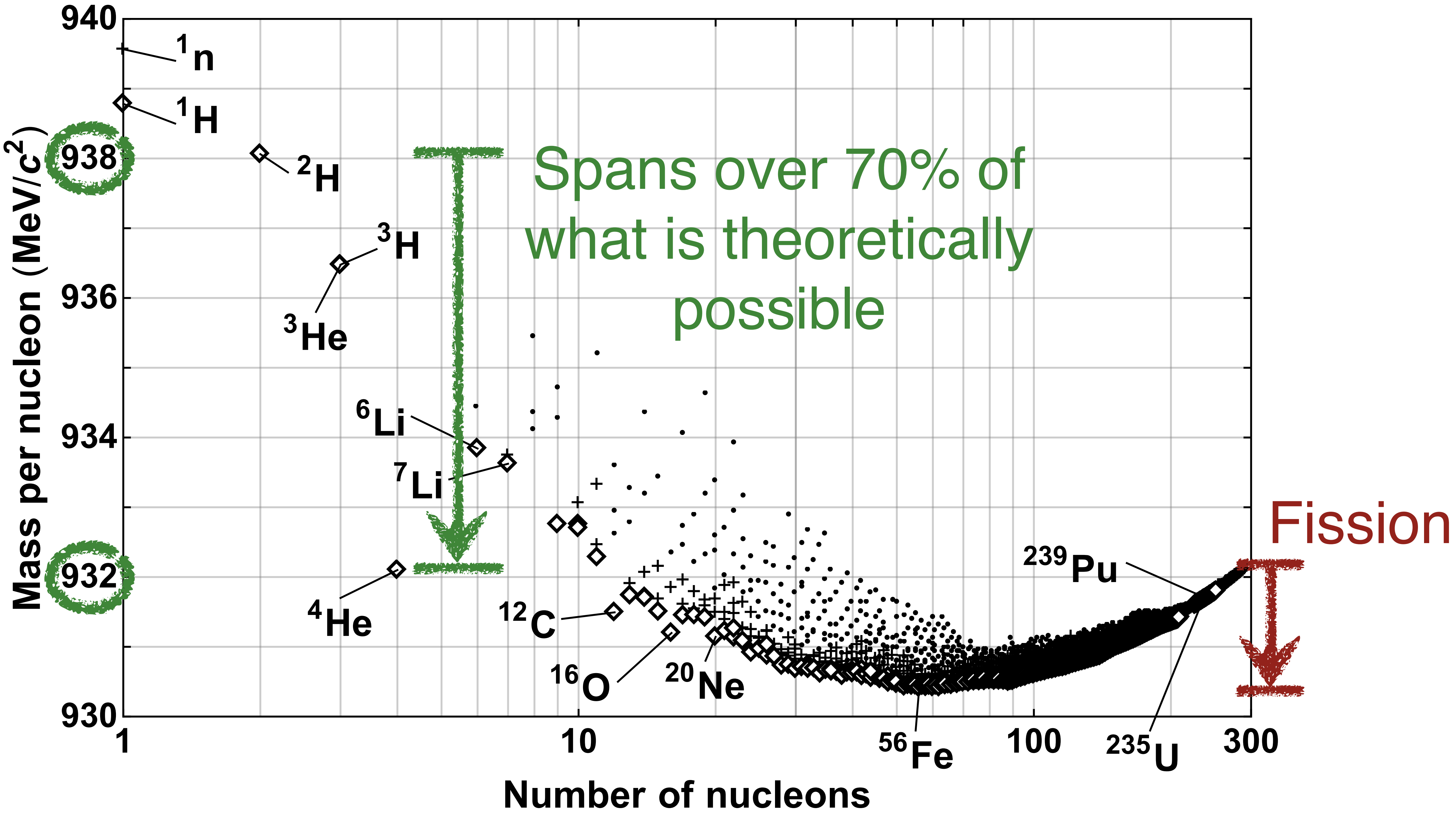
- Fusing H-1 or He-4 is extremely difficult or requires less abundant isotopes

Primordial Isotopic Abundances

Isotope	Normalized Abundance[1]
H-1	0.92
He-4	0.08
H-2	4×10^{-5}
He-3	1×10^{-5}
Li-7	3×10^{-10}

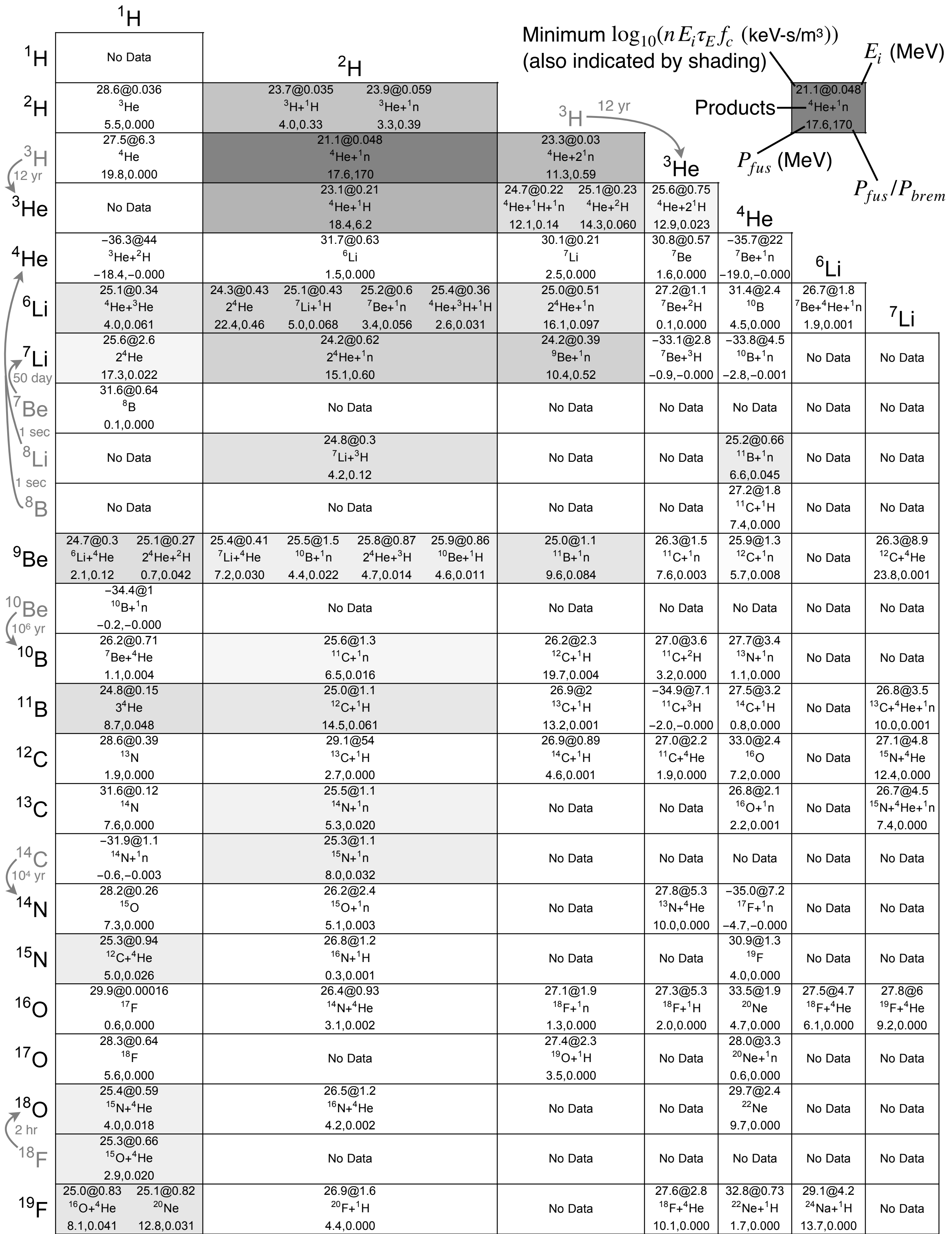
Why do we care? Specific energy

- The specific energy of **`2 D → ⁴He + 23.8MeV`** is nearly **`6MeV/AMU`**



Catalyzed D-D+D maximizes specific energy

- Systematic search of the EXFOR database
- Estimate the minimum triple products needed for ignition for **all** measured reactions
- From this you can construct a fairly rigorous proof
- Less rigorously: stars are big

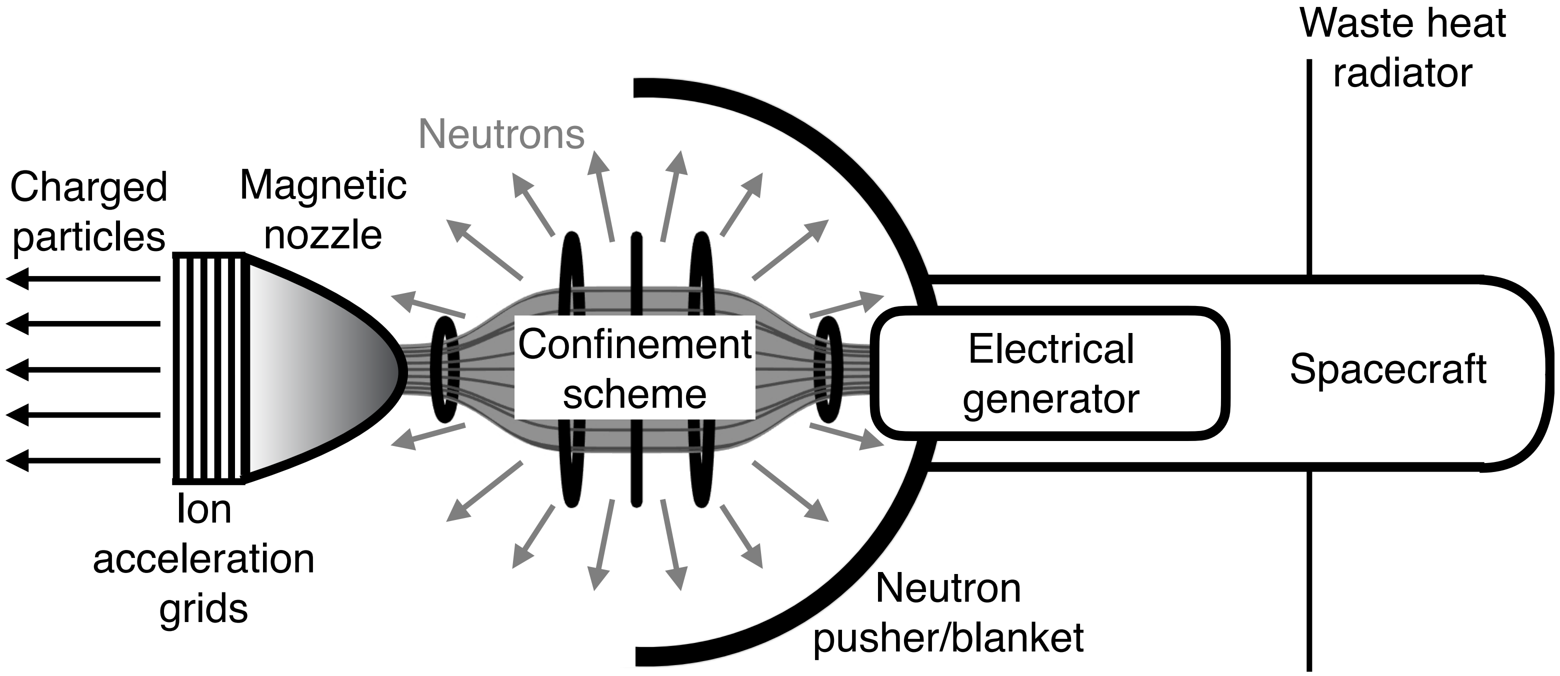


Minimum $\log_{10}(n E_i \tau_E f_c$ (keV-s/m³)) (also indicated by shading)

	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li	^{7}Li
^{1}H	No Data						
^{2}H	28.6@0.036 ^{3}He 5.5,0.000	23.7@0.035 ^{3}H+^{1}H 4.0,0.33 23.9@0.059 ^{3}He+^{1}n 3.3,0.39					
^{3}H	27.5@6.3 ^{4}He 19.8,0.000	21.1@0.048 ^{4}He+^{1}n 17.6,170	23.3@0.03 ^{4}He+2^{1}n 11.3,0.59				
^{3}He	No Data	23.1@0.21 ^{4}He+^{1}H 18.4,6.2	24.7@0.22 ^{4}He+^{1}H+^{1}n 12.1,0.14 25.1@0.23 ^{4}He+^{2}H 14.3,0.060	25.6@0.75 ^{4}He+2^{1}H 12.9,0.023			
^{4}He	−36.3@44 ^{3}He+^{2}H −18.4,−0.000	31.7@0.63 ^{6}Li 1.5,0.000	30.1@0.21 ^{7}Li 2.5,0.000	30.8@0.57 ^{7}Be 1.6,0.000	−35.7@22 ^{7}Be+^{1}n −19.0,−0.000		
^{6}Li	25.1@0.34 ^{4}He+^{3}He 4.0,0.061	24.3@0.43 2^{4}He 22.4,0.46 25.1@0.43 ^{7}Li+^{1}H 5.0,0.068 25.2@0.6 ^{7}Be+^{1}n 3.4,0.056 25.4@0.36 ^{4}He+^{3}H+^{1}H 2.6,0.031	25.0@0.51 2^{4}He+^{1}n 16.1,0.097	27.2@1.1 ^{7}Be+^{2}H 0.1,0.000	31.4@2.4 ^{10}B 4.5,0.000	26.7@1.8 ^{7}Be+^{4}He+^{1}n 1.9,0.001	
^{7}Li	25.6@2.6 2^{4}He 17.3,0.022	24.2@0.62 2^{4}He+^{1}n 15.1,0.60	24.2@0.39 ^{9}Be+^{1}n 10.4,0.52	−33.1@2.8 ^{7}Be+^{3}H −0.9,−0.000	−33.8@4.5 ^{10}B+^{1}n −2.8,−0.001	No Data	No Data
^{7}Be	31.6@0.64 ^{8}B 0.1,0.000	No Data	No Data	No Data	No Data	No Data	No Data
^{8}Li	No Data	24.8@0.3 ^{7}Li+^{3}H 4.2,0.12	No Data	No Data	25.2@0.66 ^{11}B+^{1}n 6.6,0.045	No Data	No Data
^{8}B	No Data	No Data	No Data	No Data	27.2@1.8 ^{11}C+^{1}H 7.4,0.000	No Data	No Data
^{9}Be	24.7@0.3 ^{6}Li+^{4}He 2.1,0.12 25.1@0.27 2^{4}He+^{2}H 0.7,0.042	25.4@0.41 ^{7}Li+^{4}He 7.2,0.030 25.5@1.5 ^{10}B+^{1}n 4.4,0.022 25.8@0.87 2^{4}He+^{3}H 4.7,0.014 25.9@0.86 ^{10}Be+^{1}H 4.6,0.011	25.0@1.1 ^{11}B+^{1}n 9.6,0.084	26.3@1.5 ^{11}C+^{1}n 7.6,0.003	25.9@1.3 ^{12}C+^{1}n 5.7,0.008	No Data	26.3@8.9 ^{12}C+^{4}He 23.8,0.001
^{10}Be	−34.4@1 ^{10}B+^{1}n −0.2,−0.000	No Data	No Data	No Data	No Data	No Data	No Data
^{10}B	26.2@0.71 ^{7}Be+^{4}He 1.1,0.004	25.6@1.3 ^{11}C+^{1}n 6.5,0.016	26.2@2.3 ^{12}C+^{1}H 19.7,0.004	27.0@3.6 ^{11}C+^{2}H 3.2,0.000	27.7@3.4 ^{13}N+^{1}n 1.1,0.000	No Data	No Data
^{11}B	24.8@0.15 3^{4}He 8.7,0.048	25.0@1.1 ^{12}C+^{1}H 14.5,0.061	26.9@2 ^{13}C+^{1}H 13.2,0.001	−34.9@7.1 ^{11}C+^{3}H −2.0,−0.000	27.5@3.2 ^{14}C+^{1}H 0.8,0.000	No Data	26.8@3.5 ^{13}C+^{4}He+^{1}n 10.0,0.001
^{12}C	28.6@0.39 ^{13}N 1.9,0.000	29.1@54 ^{13}C+^{1}H 2.7,0.000	26.9@0.89 ^{14}C+^{1}H 4.6,0.001	27.0@2.2 ^{11}C+^{4}He 1.9,0.000	33.0@2.4 ^{16}O 7.2,0.000	No Data	27.1@4.8 ^{15}N+^{4}He 12.4,0.000
^{13}C	31.6@0.12 ^{14}N 7.6,0.000	25.5@1.1 ^{14}N+^{1}n 5.3,0.020	No Data	No Data	26.8@2.1 ^{16}O+^{1}n 2.2,0.001	No Data	26.7@4.5 ^{15}N+^{4}He+^{1}n 7.4,0.000
^{14}C	−31.9@1.1 ^{14}N+^{1}n −0.6,−0.003	25.3@1.1 ^{15}N+^{1}n 8.0,0.032	No Data	No Data	No Data	No Data	No Data
^{14}N	28.2@0.26 ^{15}O 7.3,0.000	26.2@2.4 ^{15}O+^{1}n 5.1,0.003	No Data	27.8@5.3 ^{13}N+^{4}He 10.0,0.000	−35.0@7.2 ^{17}F+^{1}n −4.7,−0.000	No Data	No Data
^{15}N	25.3@0.94 ^{12}C+^{4}He 5.0,0.026	26.8@1.2 ^{16}N+^{1}H 0.3,0.001	No Data	No Data	30.9@1.3 ^{19}F 4.0,0.000	No Data	No Data
^{16}O	29.9@0.00016 ^{17}F 0.6,0.000	26.4@0.93 ^{14}N+^{4}He 3.1,0.002	27.1@1.9 ^{18}F+^{1}n 1.3,0.000	27.3@5.3 ^{18}F+^{1}H 2.0,0.000	33.5@1.9 ^{20}Ne 4.7,0.000	27.5@4.7 ^{18}F+^{4}He 6.1,0.000	27.8@6 ^{19}F+^{4}He 9.2,0.000
^{17}O	28.3@0.64 ^{18}F 5.6,0.000	No Data	27.4@2.3 ^{19}O+^{1}H 3.5,0.000	No Data	28.0@3.3 ^{20}Ne+^{1}n 0.6,0.000	No Data	No Data
^{18}O	25.4@0.59 ^{15}N+^{4}He 4.0,0.018	26.5@1.2 ^{16}N+^{4}He 4.2,0.002	No Data	No Data	29.7@2.4 ^{22}Ne 9.7,0.000	No Data	No Data
^{18}F	25.3@0.66 ^{15}O+^{4}He 2.9,0.020	No Data	No Data	No Data	No Data	No Data	No Data
^{19}F	25.0@0.83 ^{16}O+^{4}He 8.1,0.041 25.1@0.82 ^{20}Ne 12.8,0.031	26.9@1.6 ^{20}F+^{1}H 4.4,0.000	No Data	27.6@2.8 ^{18}F+^{4}He 10.1,0.000	32.8@0.73 ^{22}Ne+^{1}H 1.7,0.000	29.1@4.2 ^{24}Na+^{1}H 13.7,0.000	No Data

Why do we care? Interstellar space travel

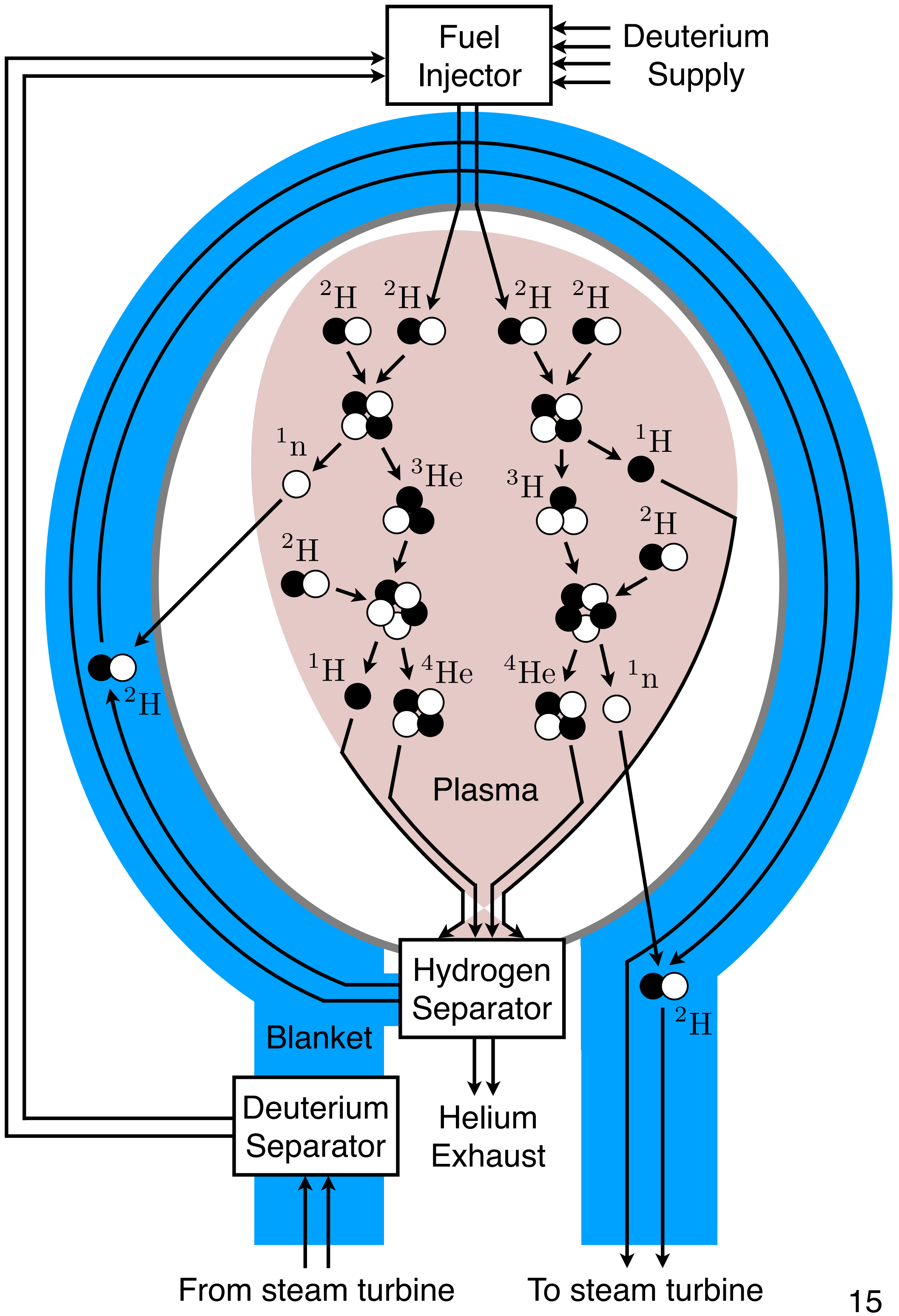
- Specific *momentum*, rather than energy is key



- D-He-3 is the “conventional” fuel for propulsion because:
  - Only produces charged particles
  - **<u>Was</u>** thought to have the highest specific momentum (7.1% of the speed of light)
- Theoretically, catalyzed D-D+D can achieve 11.3%, but neutrons are hard to direct and hydrogen must be kept onboard to breed deuterium

Important caveat regarding specific energy

- High specific energy is only useful if the mass of the fuel actually matters
- For many applications, all fusion fuels are so energy dense that their mass is negligible
- A half meter thick breeding blanket may weigh 1,000 times more than the deuterium it breeds each year
- Nevertheless, fuel mass would be more significant for large, durable fusion devices with high power densities



Conclusions

- Given the ability to achieve the catalyzed D-D fuel cycle, achieving the catalyzed D-D+D fuel cycle is straightforward

- Such a fuel cycle:

    - enables a given quantity of deuterium to generate as much as 65% more energy

    - has the highest specific energy of any known generation scheme

    - useful where structural material is abundant, but not fuel (e.g. asteroid mining, transmission stations, large construction projects)

    - theoretically enables a spacecraft to have a specific momentum exceeding D-He-3

Questions?

J. Ball. “Maximizing specific energy by breeding deuterium.”
Nuclear Fusion **59** 106043 (2019).