Is There a Better Route to Fusion?

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LLNL High Energy Density Science Seminar

> "Thirty-five years ago I was an expert precious-metal quartz-miner. There was an outcrop in my neighborhood that assayed $600 a ton—gold. But every fleck of gold in it was shut up tight and fast in an intractable and impersuadable base-metal shell. Acting as a Consensus, I delivered the finality verdict that no human ingenuity would ever be able to set free two dollars' worth of gold out of a ton of that rock. The fact is, I did not foresee the cyanide process… These sorrows have made me suspicious of Consensuses… I sheer warily off and get behind something, saying to myself, 'It looks innocent and all right, but no matter, ten to one there's a cyanide process under that thing somewhere.'"
>
> -Mark Twain, "Dr. Loeb's Incredible Discovery" (1910)

Motivation

Current fission power approaches are not ideal

- **Politically incorrect amount of radioactivity during and long after operation**
- **Conventional reactors are very expensive [>$10B each]**

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➔ We will try to “rederive” nuclear power from first principles, looking for better approaches at each step along the way.

Wish List of Characteristics
For the Perfect Nuclear Energy Source

- Little or no radiation and radioactive waste
- Minimal shielding
- Scalable to power everything from computer chips to GW reactors
- High-efficiency direct conversion to electricity
- Utilizes readily available fuel
- Cannot explode, melt down, or frighten Jane Fonda
- Not directly or indirectly useful to terrorists or unfriendly countries

Can we come closer to meeting these goals?

Nuclear vs. Chemical Energy

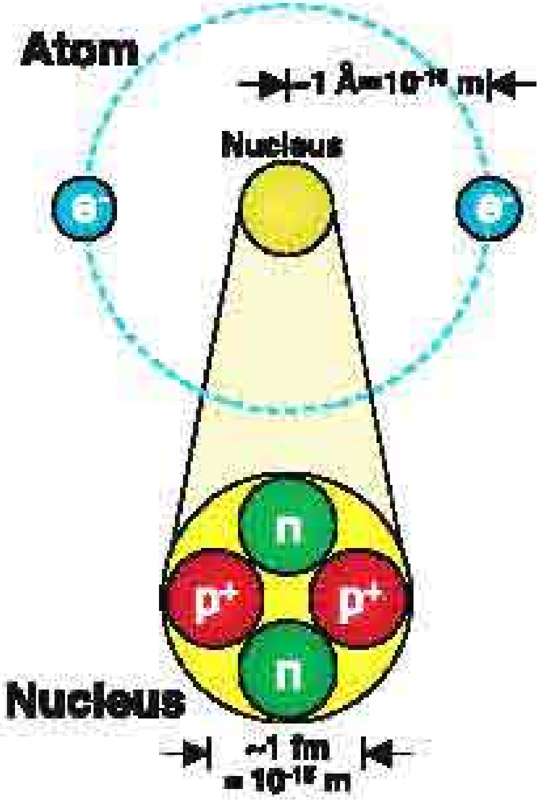
From Coulomb's law:

$$E \sim \frac{e^2}{4\pi\varepsilon_o r}$$

$$= \frac{14.4\ \text{eV}}{r\ \ [\text{in Å}]}$$

$$\frac{E_{nucl}}{E_{chem}} \sim \frac{r_{atom}}{r_{nucl}} \sim 10^5$$

(Valid since strong force ~ Coulomb force in nucleus)



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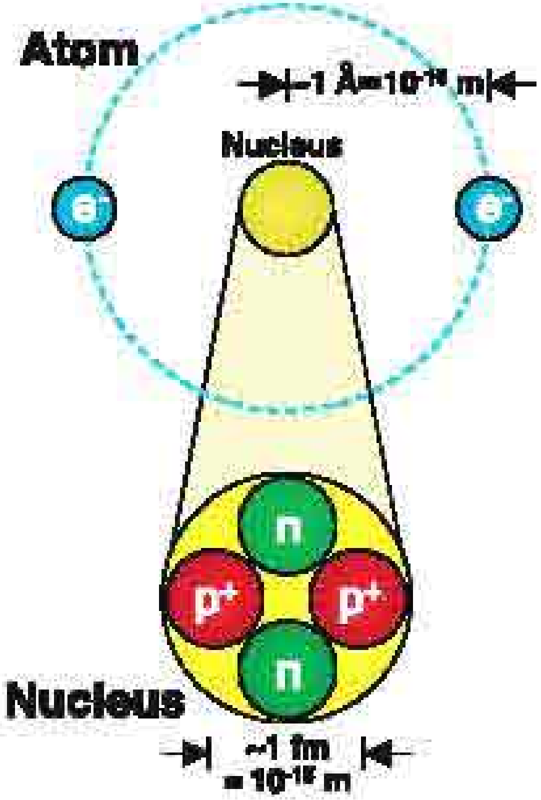

From Heisenberg uncertainty principle:

$$(\Delta p)\ (\Delta x) \sim \hbar$$

$$E \sim \frac{(\Delta p)^2}{2m} = \frac{\hbar^2}{2m(\Delta x)^2}$$

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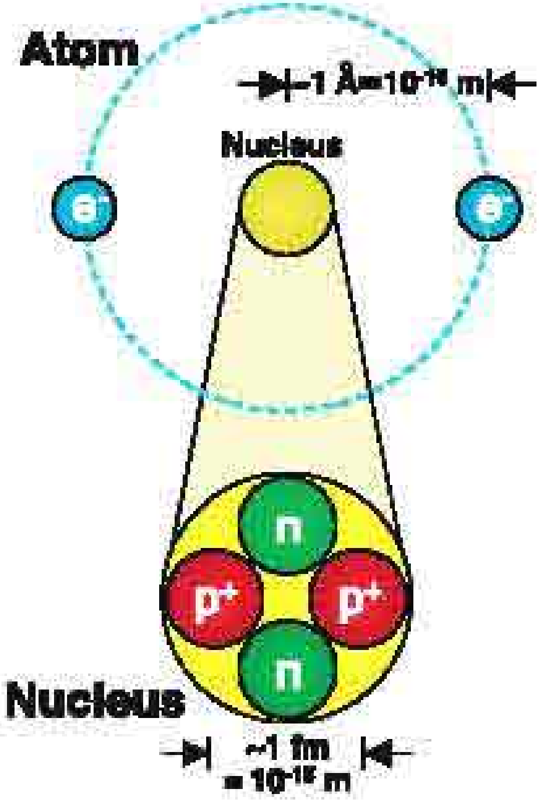

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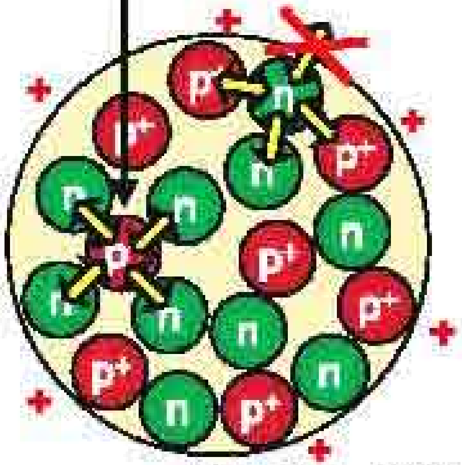
- **Nuclear processes rearrange protons & neutrons and release ~10^5-10^6 more energy than chemical reactions, which rearrange atomic electrons (MeV vs. eV)**
- **A nuclear particle has enough energy to break ~10^5-10^6 chemical bonds**
  - **Can damage reactor components, depending on particle type & component material**
  - **Especially bad for DNA and other biological molecules**

Contributions to Nuclear Binding Energy E_B (in MeV)

$E_B = 16\ A$

Average binding energy of nucleon with nearest neighbors (strong force range ~1.5 fm)



Valid for $A \geq 16$

Radius ~ $A^{1/3}$

Surface area ~ $A^{2/3}$

Volume ~ A

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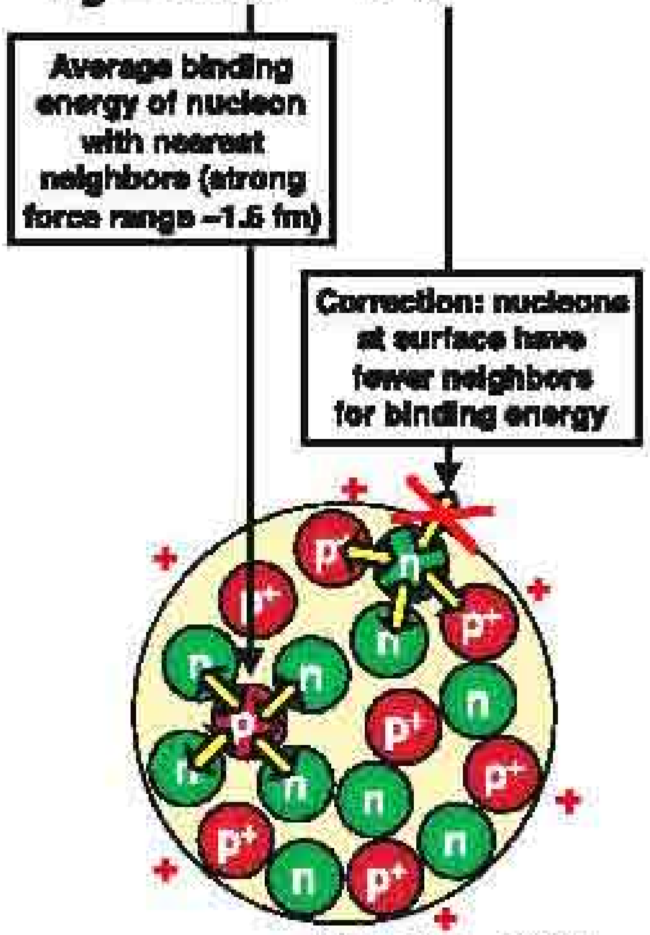

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Correction: nucleons at surface have fewer neighbors for binding energy

Valid for
A ≥ 15

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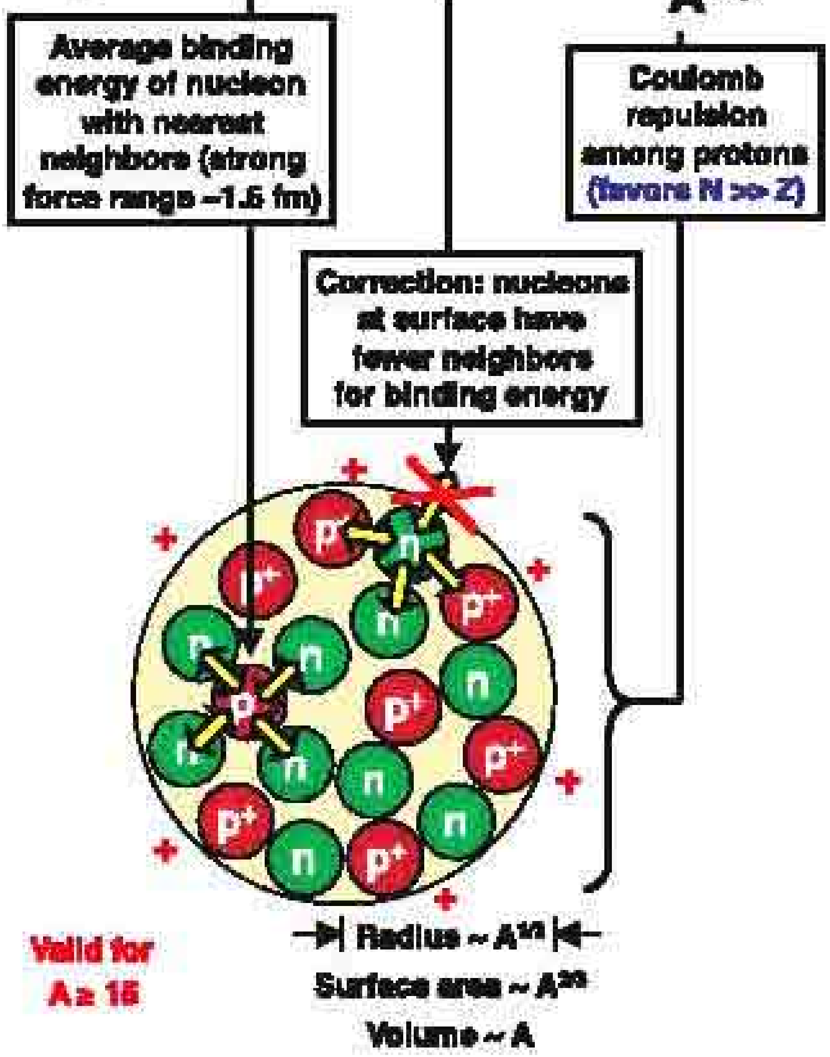
Contributions to Nuclear Binding Energy E_B (in MeV)

$$E_B = 16\,A \quad - 17\,A^{2/3} \quad - 0.7\,\frac{Z^2}{A^{1/3}}$$



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Valid for A ≥ 16

Contributions to Nuclear Binding Energy E_B (in MeV)

$$E_B = 16\,A \quad - 17\,A^{2/3} \quad - 0.7\,\frac{Z^2}{A^{1/3}} \quad - 25\,\frac{(N - Z)^2}{A}$$

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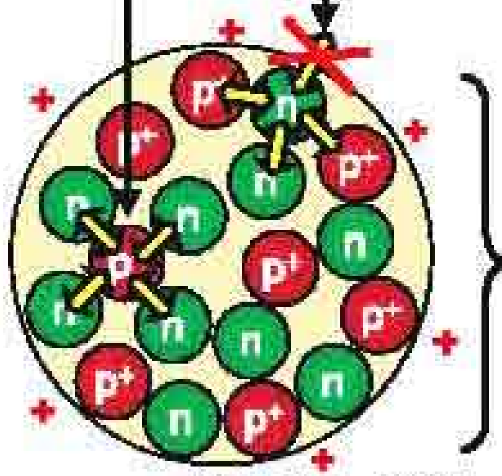
Energy cost of not filling neutron and proton states to same level (favors N ~ Z)



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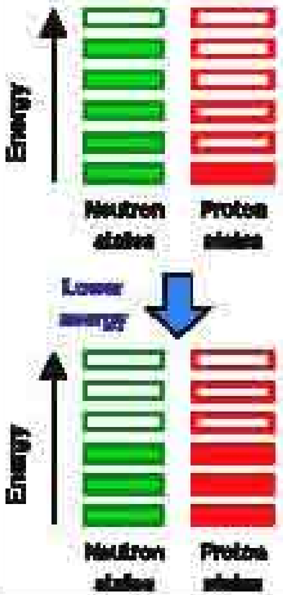

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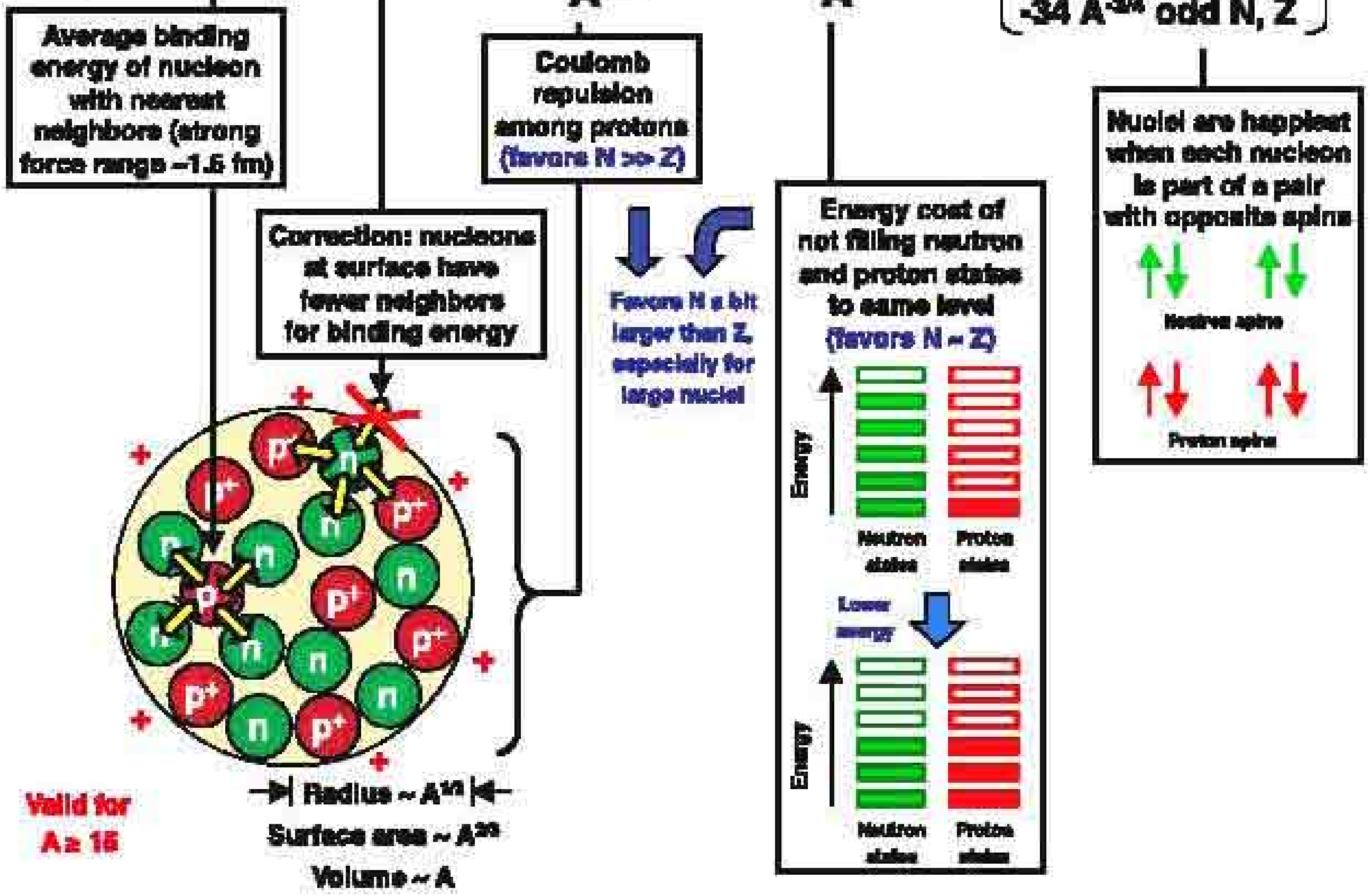
$$E_B = 16\,A \;-\; 17\,A^{2/3} \;-\; 0.7\,\frac{Z^2}{A^{1/3}} \;-\; 25\,\frac{(N-Z)^2}{A} \;+\; \left\{\begin{array}{ll} 34\,A^{-3/4} & \text{even N, Z} \\ 0 & \text{odd-even} \\ -34\,A^{-3/4} & \text{odd N, Z} \end{array}\right\}$$



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If N or Z is magic

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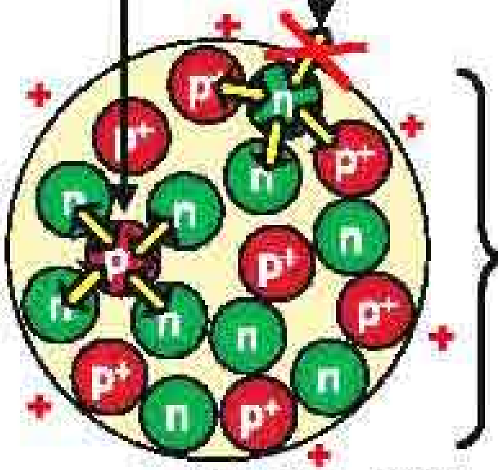
Bonus for filled nucleon energy shells at magic numbers of N and Z: 2, 8, 20, 28, 50, 82, 126, ... (similar to atomic electron shells)



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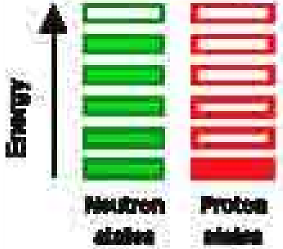
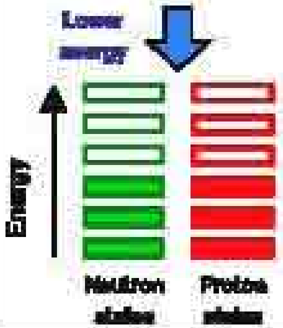
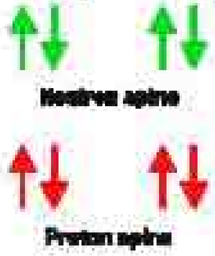
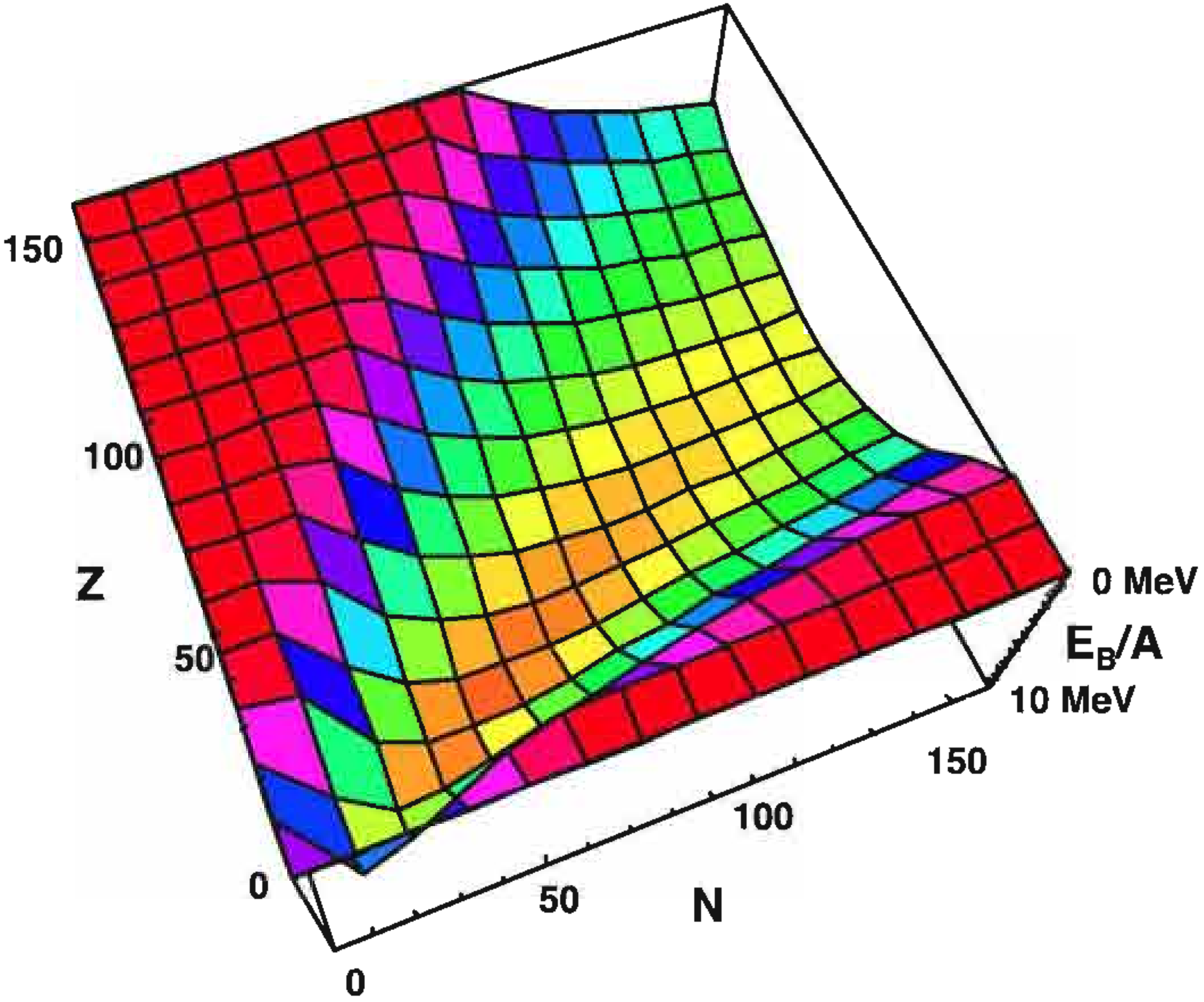






Binding Energy per Nucleon
And Methods of Tapping It



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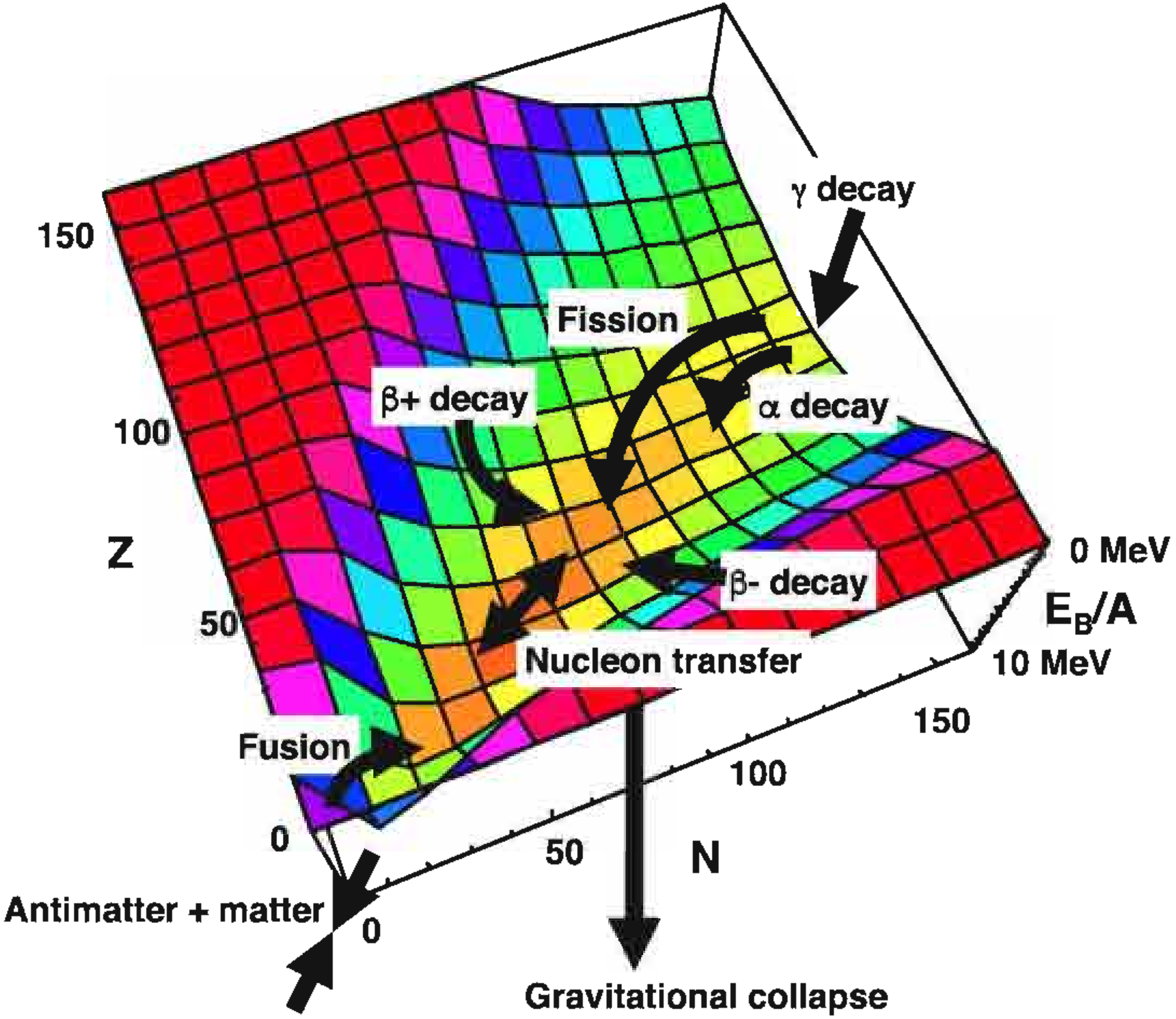

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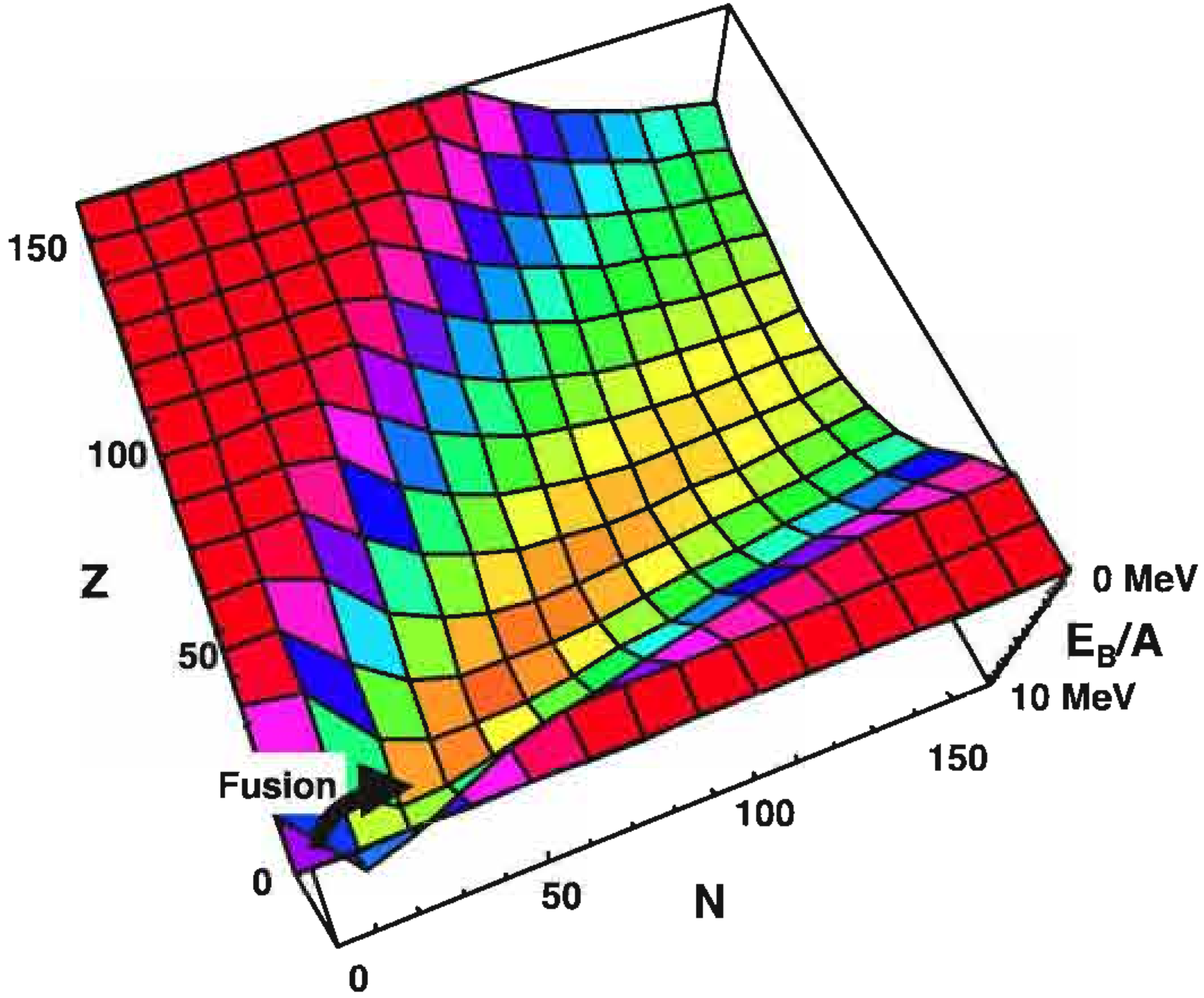
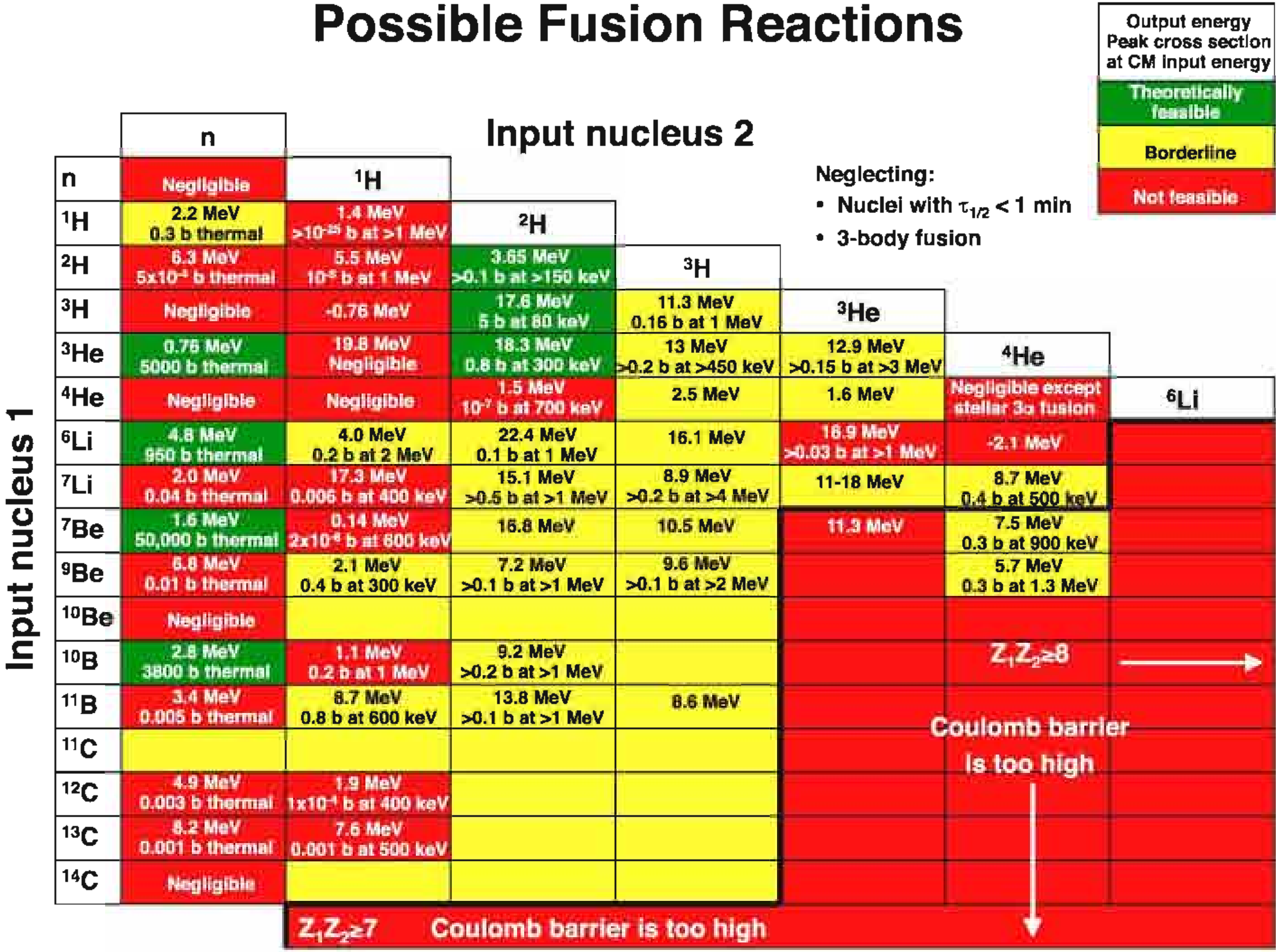


Possible Fusion Reactions



Output energy
Peak cross section
at CM input energy

🟩 Theoretically feasible

🟨 Borderline

🟥 Not feasible

Neglecting:

- Nuclei with $\tau_{1/2} < 1$ min
- 3-body fusion

Input nucleus 2 (columns) / **Input nucleus 1** (rows)

Input nucleus 1	n	^{1}H	^{2}H	^{3}H	^{3}He	^{4}He	^{6}Li
n	Negligible						
^{1}H	2.2 MeV 0.3 b thermal	1.4 MeV $>10^{-25}$ b at >1 MeV					
^{2}H	6.3 MeV 5×10^{-4} b thermal	5.5 MeV 10^{-5} b at 1 MeV	3.65 MeV >0.1 b at >150 keV				
^{3}H	Negligible	-0.76 MeV	17.6 MeV 5 b at 80 keV	11.3 MeV 0.16 b at 1 MeV			
^{3}He	0.76 MeV 5000 b thermal	19.8 MeV Negligible	18.3 MeV 0.8 b at 300 keV	13 MeV >0.2 b at >450 keV	12.9 MeV >0.15 b at >3 MeV		
^{4}He	Negligible	Negligible	1.5 MeV 10^{-7} b at 700 keV	2.5 MeV	1.6 MeV	Negligible except stellar 3α fusion	
^{6}Li	4.8 MeV 950 b thermal	4.0 MeV 0.2 b at 2 MeV	22.4 MeV 0.1 b at 1 MeV	16.1 MeV	16.9 MeV >0.03 b at >1 MeV	-2.1 MeV	
^{7}Li	2.0 MeV 0.04 b thermal	17.3 MeV 0.006 b at 400 keV	15.1 MeV >0.5 b at >1 MeV	8.9 MeV >0.2 b at >4 MeV	11-18 MeV	8.7 MeV 0.4 b at 500 keV	
^{7}Be	1.6 MeV 50,000 b thermal	0.14 MeV 2×10^{-6} b at 600 keV	16.8 MeV	10.5 MeV	11.3 MeV	7.5 MeV 0.3 b at 900 keV	
^{9}Be	6.8 MeV 0.01 b thermal	2.1 MeV 0.4 b at 300 keV	7.2 MeV >0.1 b at >1 MeV	9.6 MeV >0.1 b at >2 MeV		5.7 MeV 0.3 b at 1.3 MeV	
^{10}Be	Negligible						
^{10}B	2.8 MeV 3800 b thermal	1.1 MeV 0.2 b at 1 MeV	9.2 MeV >0.2 b at >1 MeV				
^{11}B	3.4 MeV 0.005 b thermal	8.7 MeV 0.8 b at 600 keV	13.8 MeV >0.1 b at >1 MeV	8.6 MeV			
^{11}C							
^{12}C	4.9 MeV 0.003 b thermal	1.9 MeV 1×10^{-4} b at 400 keV					
^{13}C	8.2 MeV 0.001 b thermal	7.6 MeV 0.001 b at 500 keV					
^{14}C	Negligible						

$Z_1Z_2\geq8$ →

Coulomb barrier is too high

$Z_1Z_2\geq7$ Coulomb barrier is too high

Physical Factors in Fusion Cross Section (in barns)

As a Function of Center-of-Mass Energy E_{CM} (keV)

$\sigma_{fus}=$

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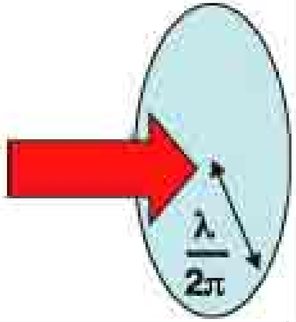
$$A_{red} = \frac{A_1 A_2}{(A_1 + A_2)}$$

Diffraction-limited cross-sectional area $\pi\,(\lambda/2\pi)^2$ for wavefunctions of colliding nuclei



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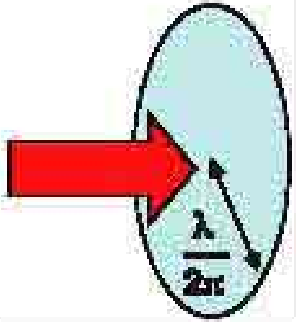
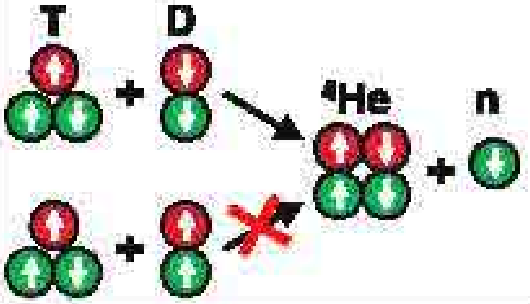


Input nuclei must have correct spins to fuse

Sum over 2J+1 possible spin states of compound nucleus and average over $(2J_1+1)$ and $(2J_2+1)$ spin states of each input nucleus

2/3 for unpolarized D+T or D+^{3}He



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Probability of tunneling through Coulomb barrier between nuclei

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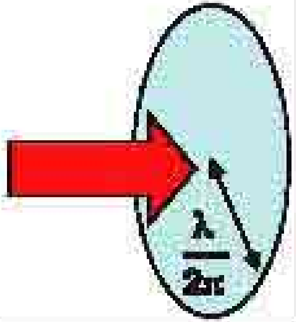

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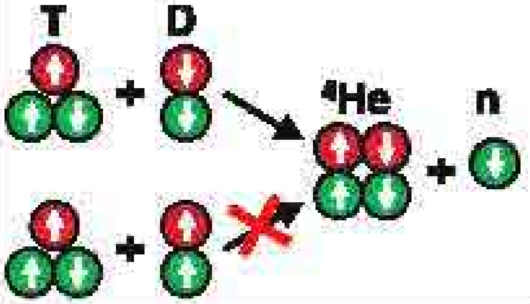

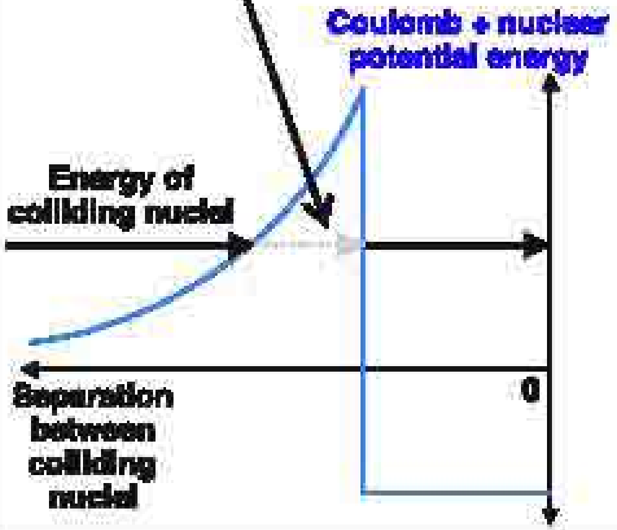

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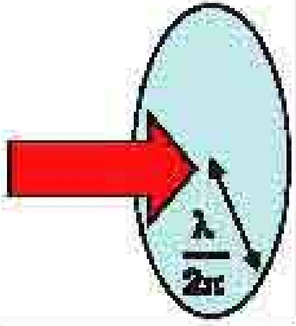

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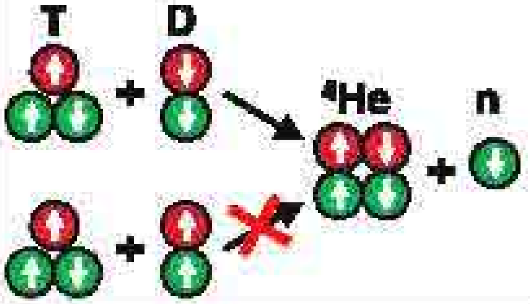

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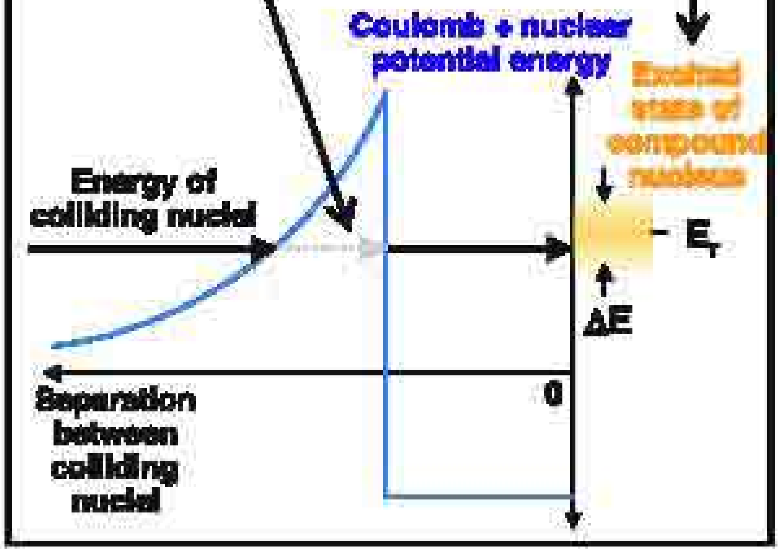
Collision energy E_{CM} must be within ~$\Delta E/2$ of excited state energy E_r of compound nucleus



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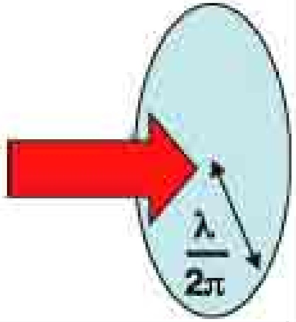

Are there any ways to improve or alter this factor other than its obvious dependence on A_{red} and E_{CM}?

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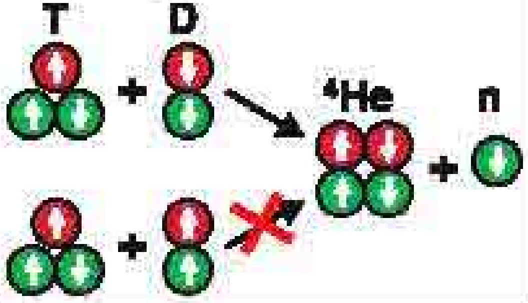

Need better evidence (esp. experimental) for/against:

- Potential benefits of spin-polarized nuclei
  - Increase σ_{fus} by ~50% for most fusion fuels
  - Suppress D+D side reactions in D+^{3}He plasmas
  - Control angular distribution of products
- Methods of producing spin-polarized nuclei
  - Spin-exchange optical pumping
  - Cryogenic, neutral beam, and other methods
- Depolarization mechanisms
  - Interactions with first wall
  - Magnetic inhomogeneities or fluctuations
  - Interactions with waves
  - Spin-orbit and spin-spin interactions
  - Long-range three-body collisions

Brunelli & Leotta 1987, *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei.*
Coppi et al 1986, *Phys. Fluids* 29:4060. Greenside et al 1984, *J. Vac. Sci. Technol. A* 2:619.
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Zhang & Balescu 1988, *J. Plasma Physics* 40:199 & 215.

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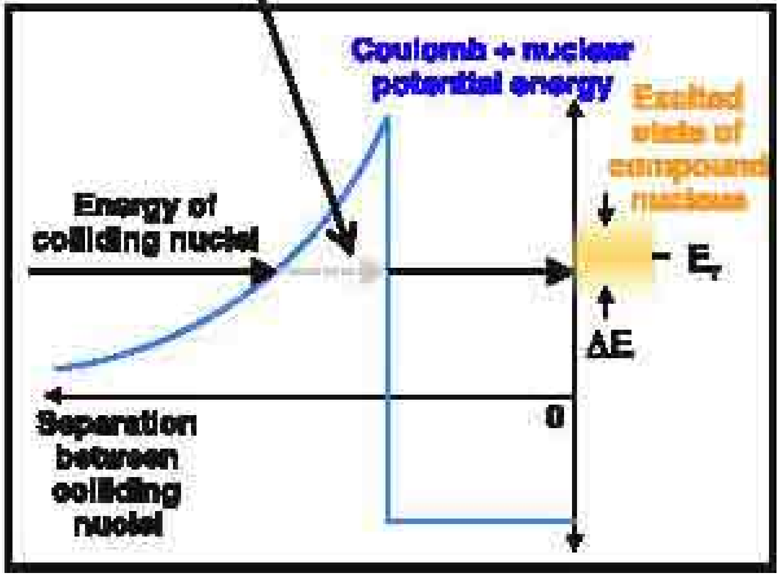
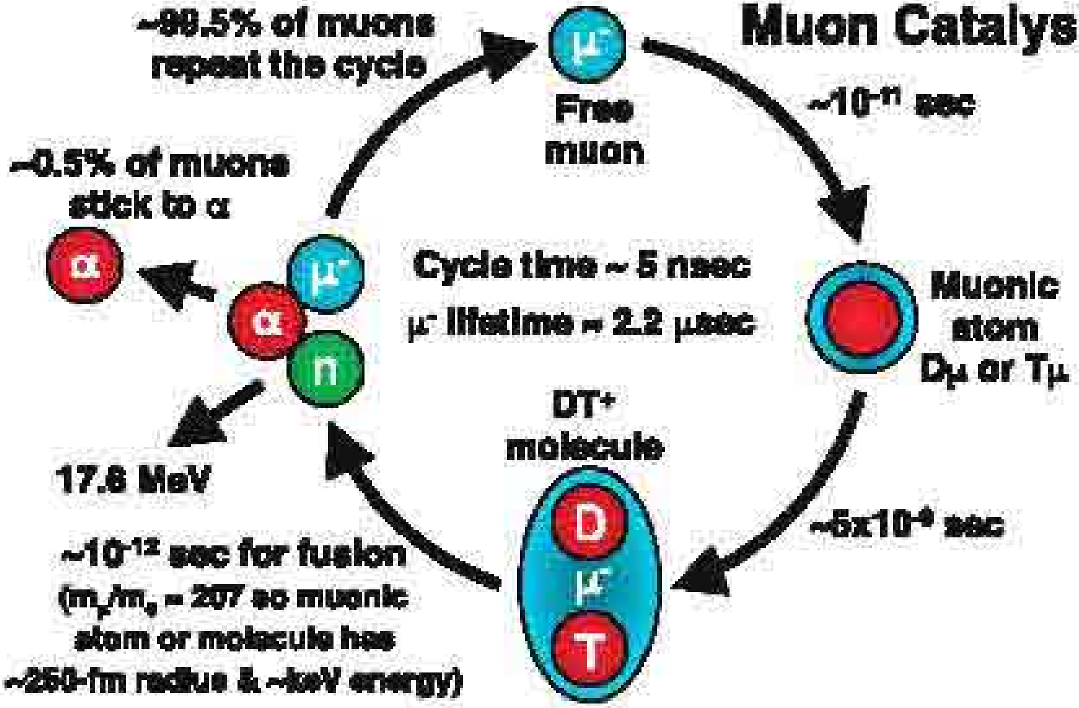
Probability of tunneling through Coulomb barrier between nuclei

Shave the outer edge of the Coulomb barrier



Shave the Outer Edge of the Coulomb Barrier

Muon Catalysis [1]



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[5] Yakovlev & Shalybkov 1987, *Sov. Astron. Lett.* 13:4:308. Ichimaru 1993, *Rev. Mod. Phys.* 65:255. Aliotta & Langanke 2022, *Frontiers in Physics* 10:942785.

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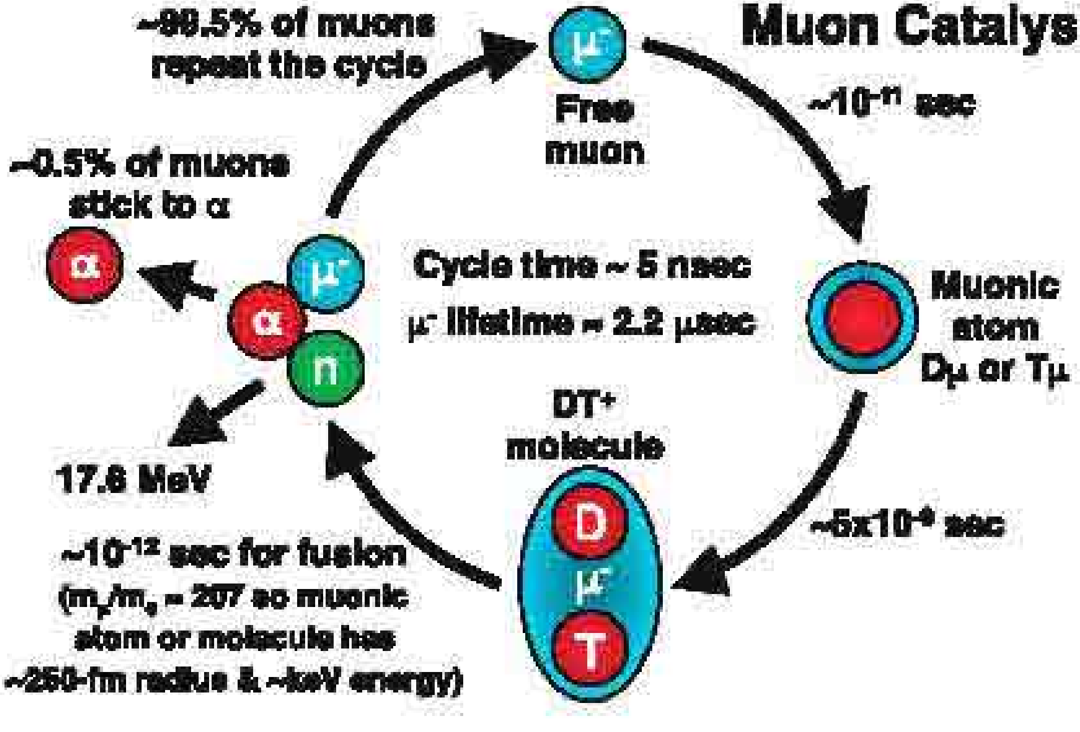

~99.5% of muons repeat the cycle

Free muon

~10^{-11} sec

Muonic atom Dμ or Tμ

~5x10^{-9} sec

DT+ molecule

~10^{-12} sec for fusion (m_μ/m_e ≈ 207 so muonic atom or molecule has ~250-fm radius & ~keV energy)

17.6 MeV

~0.5% of muons stick to α

Cycle time ~ 5 nsec

μ- lifetime ≈ 2.2 μsec

Input (μ^-) Energy

(μ^- rest energy	106 MeV)
Made from π^-	139 MeV
Make stuff other than π^-	x 10
Lab vs. CM frame	x 2
Accelerator efficiency	x 2

Present μ^- production ~5 GeV

Need more efficient methods

Output (Fusion) Energy

1 μ^- catalyzes ~(0.5%)$^{-1}$ ≈ 200 fusions before sticking to α

200 fusions x 17.6 MeV x 1/3 effic.
≈ 1 GeV useful output per μ^-

Need unsticking methods

Could then catalyze 2.2μs / 5ns
≈ 440 fusions before μ^- decays

Need way to reduce cycle time [2]

Performance is much worse for reactions other than D+T

---

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Shave the Outer Edge of the Coulomb Barrier

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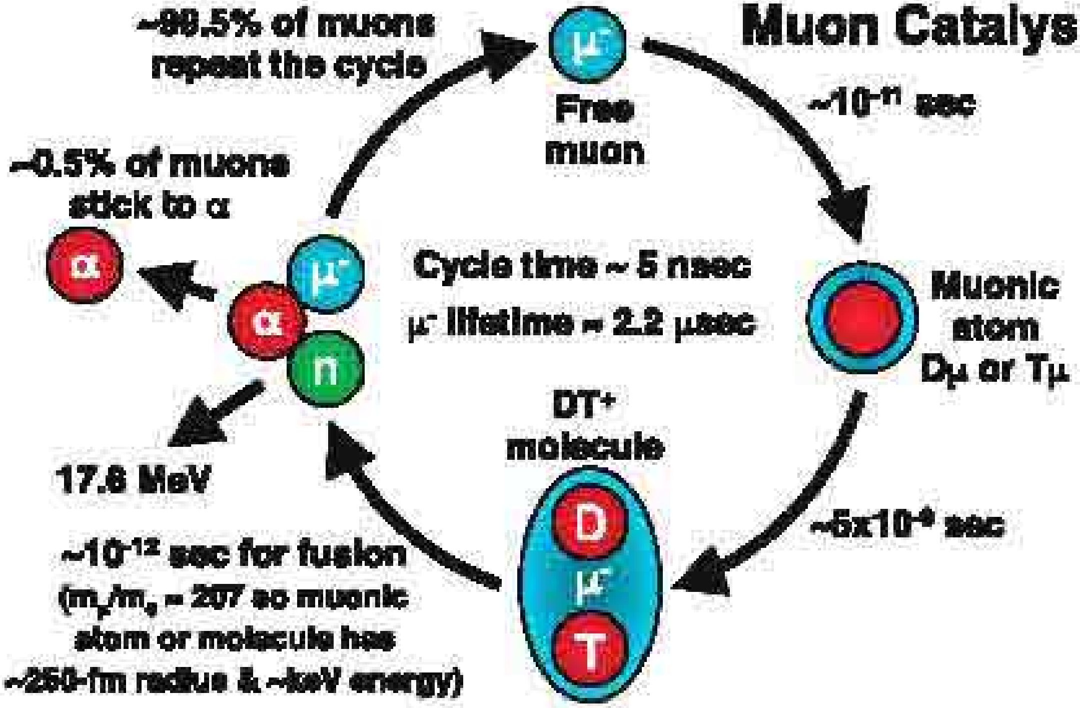

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μ^-

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~10^{-11} sec

Muonic atom Dμ or Tμ

~5×10^{-9} sec

DT$^+$ molecule

D

μ^-

T

~10^{-12} sec for fusion ($m_\mu/m_e \approx 207$ so muonic atom or molecule has ~250-fm radius & ~keV energy)

17.6 MeV

~0.5% of muons stick to α

α

μ^-

α

n

Cycle time ~ 5 nsec

μ^- lifetime ≈ 2.2 μsec

Other negative particles to reduce Coulomb barrier:

- Tau particles are harder to produce and shorter-lived than μ^-
- Antiprotons are a loser [3]
- Large effective e^- mass or charge in solids does not help [4]
- Regular electrons provide <<1 keV of screening unless one can achieve conditions comparable to a white dwarf [5]

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(μ^- rest energy	106 MeV)
Made from π^-	139 MeV
Make stuff other than π^-	x 10
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Physical Factors in Fusion Cross Section (in barns)

As a Function of Center-of-Mass Energy E_{CM} (keV)

$$\sigma_{fus} = \frac{650}{A_{red}E_{CM}} \frac{(2J+1)}{(2J_1+1)(2J_2+1)} \exp\left[-31.4Z_1Z_2\sqrt{\frac{A_{red}}{E_{CN}}} + 1.154\sqrt{Z_1Z_2A_{red}(A_1{}^{1/3}+A_2{}^{1/3})}\right] \frac{(\Delta E)^2}{(E_{CM}-E_r)^2+(\Delta E/2)^2}$$

2x increase

1.5

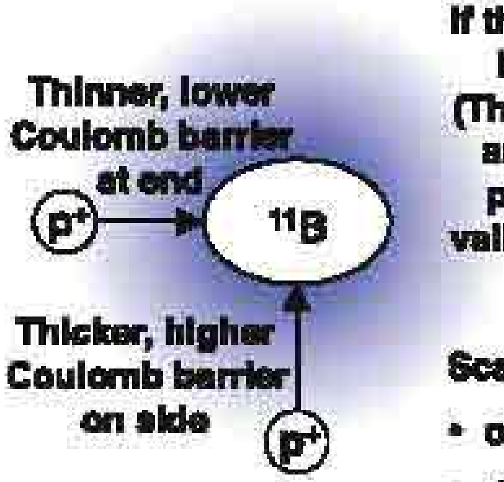
Probability of tunneling through Coulomb barrier between nuclei

Shave the inner edge of the Coulomb barrier

Shape-polarized fusion

L.J. Perkins 1997,
Phys. Lett. A 236:345.

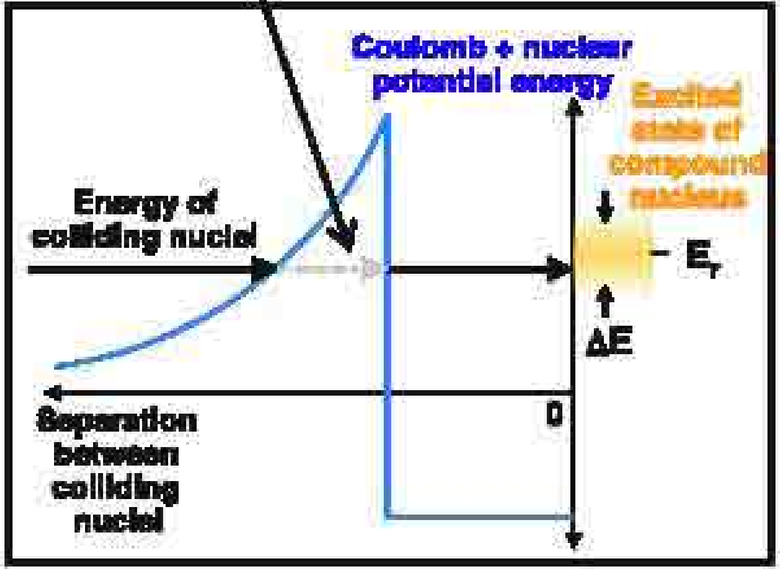
For ion energies up to several hundred keV, σ_{fus} for end-only is ~2x larger than angle-averaged σ_{fus} if the effective ^{11}B radius increases by ~1.5x. (The original paper used an inverted parabolic potential that is only valid at higher energies.)



Scattering randomizes:

- orientation of ^{11}B nuclei
- direction of p⁺ velocities

much faster than fusion



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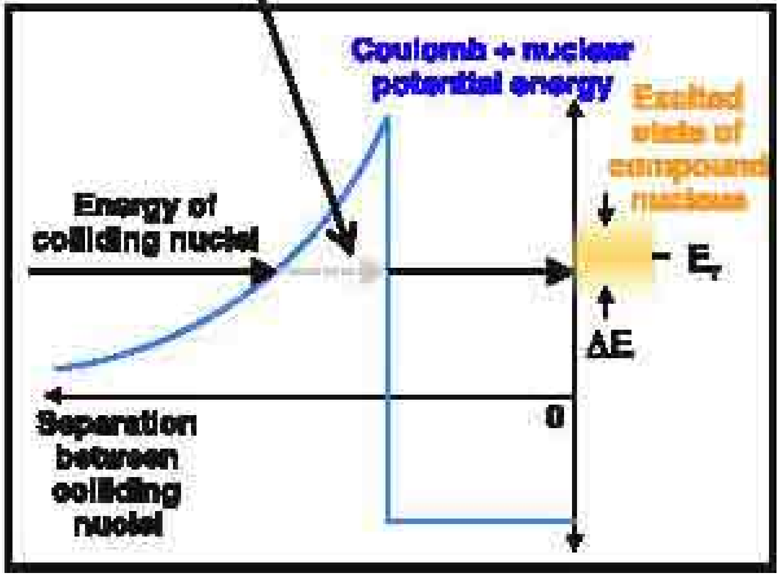
Probability of tunneling through Coulomb barrier between nuclei

Are there other ways to beat the Coulomb barrier?



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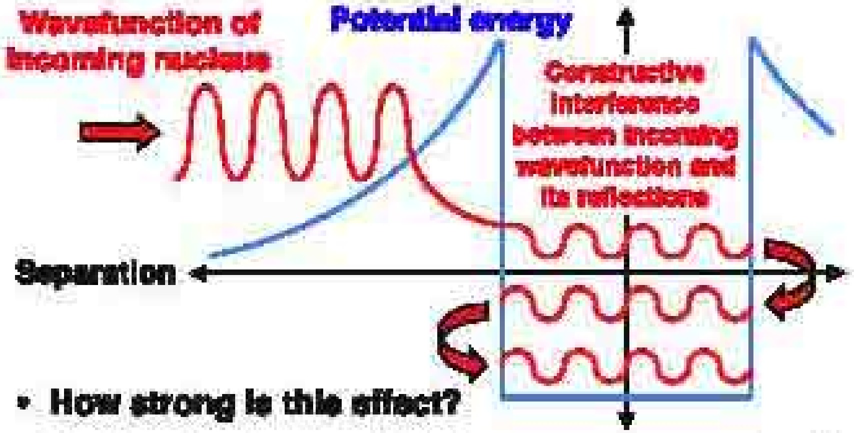
Probability of tunneling through Coulomb barrier between nuclei

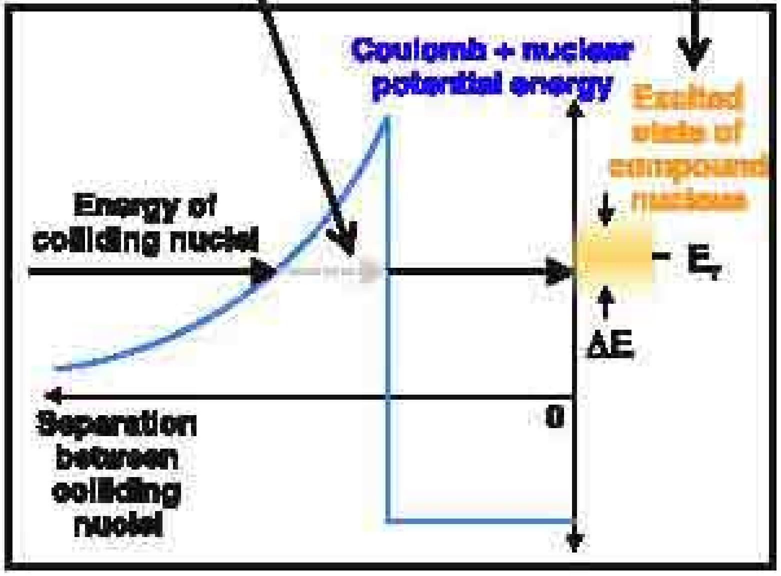
Collision energy E_{CM} must be within ~$\Delta E/2$ of excited state energy E_r of compound nucleus

Resonant tunneling

Li et al 2000, *Physical Review C* 61:024610.
Li 2002, *Fusion Science and Technology* 41:1:63.
Li et al 2004, *Journal of Fusion Energy* 23:3:217.
Li et al 2004, *Laser and Particle Beams* 22:4:469.
Li et al 2008, *Nuclear Fusion* 48:12:125003.
Li et al 2012, *Journal of Fusion Energy* 31:5:432.
Singh et al. 2019, *Nuclear Physics A* 986:98.



- How strong is this effect?
- Is this already part of the known cross sections?
- Is the resonant energy too narrow or too high to be useful?



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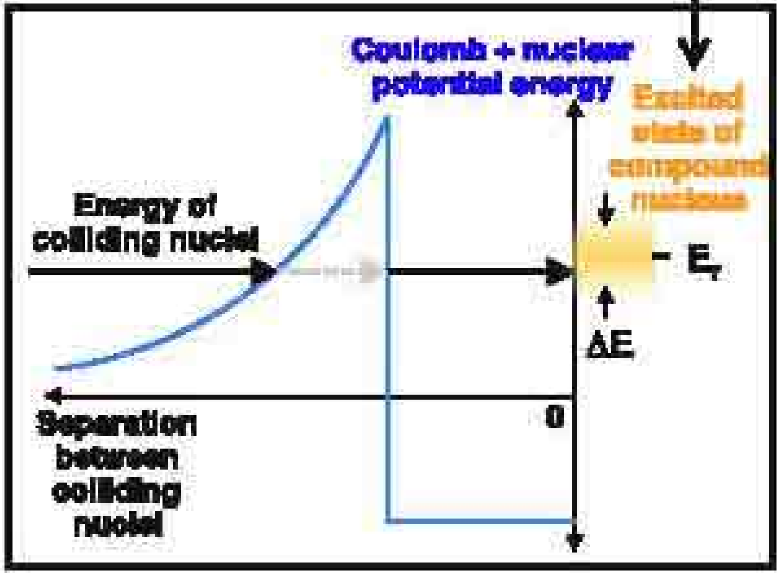
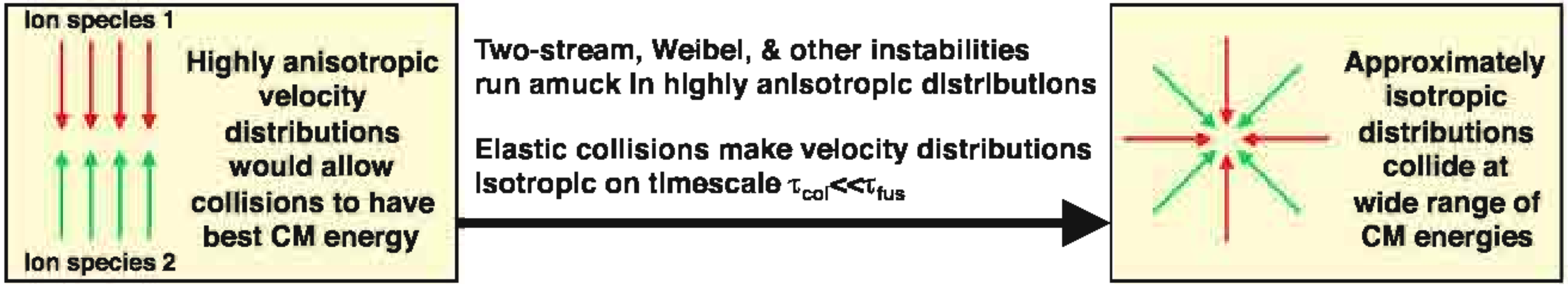
Are there any practical ways to create, heighten, broaden, or energy-shift a resonance of the compound nucleus?

- Resonances are controlled by the properties of the nucleus, which probably cannot be altered much without ~MeV of input energy, which would likely be prohibitively large. Nonetheless, it is good to consider all possibilities and conclusively rule them in or out.
- Could nuclear angular momentum be altered enough to temporarily create or modify a resonance?
- Could the shape of the nucleus be altered enough?
- Could the magic numbers be altered enough?
- Could sufficiently strong electric, magnetic, electromagnetic, and/or other fields perturb nuclear states enough?
- Could the capture of a neutron, electron, proton, positron, antiproton, antineutron, or other particle by the nucleus be sufficient and practical?
- Could extra energy be added to the nucleus (via gamma rays, neutrons, or other means), then efficiently extracted along with the usual fusion energy?

Collision energy E_{CM} must be within ~$\Delta E/2$ of excited state energy E_r of compound nucleus



Why Ions Won’t Behave



What you want:

Ion species 1

Highly anisotropic velocity distributions would allow collisions to have best CM energy

Ion species 2

Why you can’t have it:

Two-stream, Weibel, & other instabilities run amuck in highly anisotropic distributions

Elastic collisions make velocity distributions isotropic on timescale $\tau_{col} << \tau_{fus}$

What you’re stuck with:

Approximately isotropic distributions collide at wide range of CM energies

T. H. Rider, *Phys. Plasmas* 4:1039 (1997) and Ph.D. thesis, MIT (1995)

Why Ions Won't Behave

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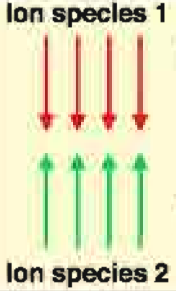

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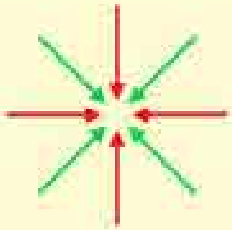

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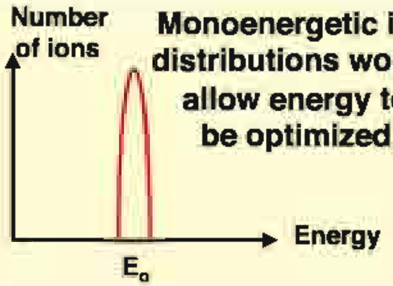
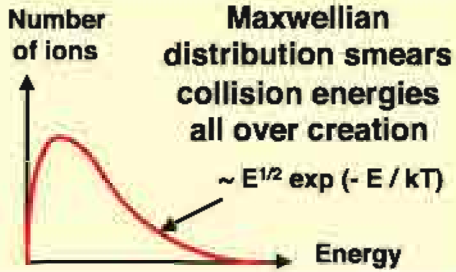


Monoenergetic ion distributions would allow energy to be optimized

Elastic collisions make ion distributions Maxwellian on timescale $\tau_{col} \ll \tau_{fus}$



Maxwellian distribution smears collision energies all over creation

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Why Ions Won't Behave

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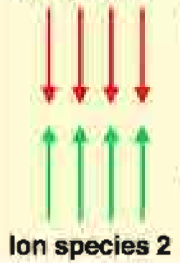

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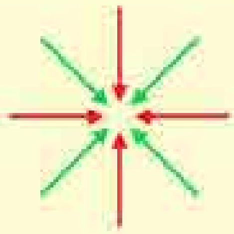

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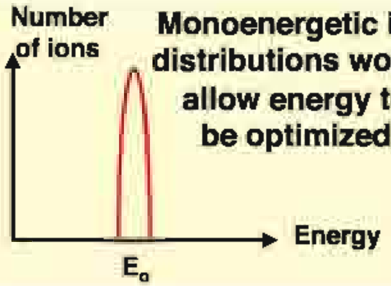

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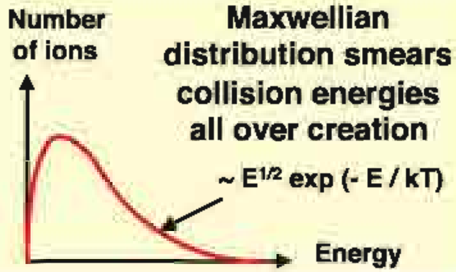

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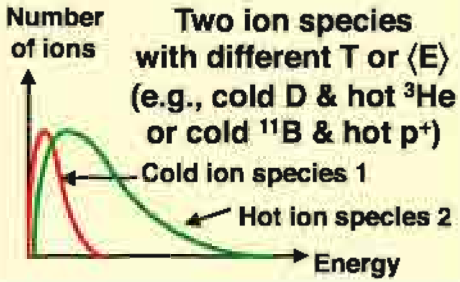
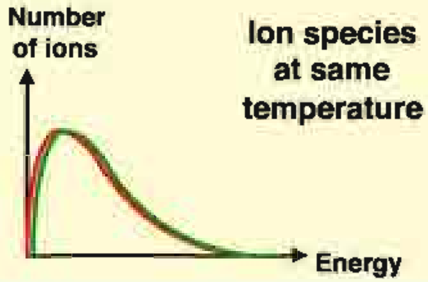


Two ion species with different T or $\langle E \rangle$ (e.g., cold D & hot ^{3}He or cold ^{11}B & hot p^+)

Collisions equilibrate temperatures of two ion species on timescale $\tau_{col} \ll \tau_{fus}$

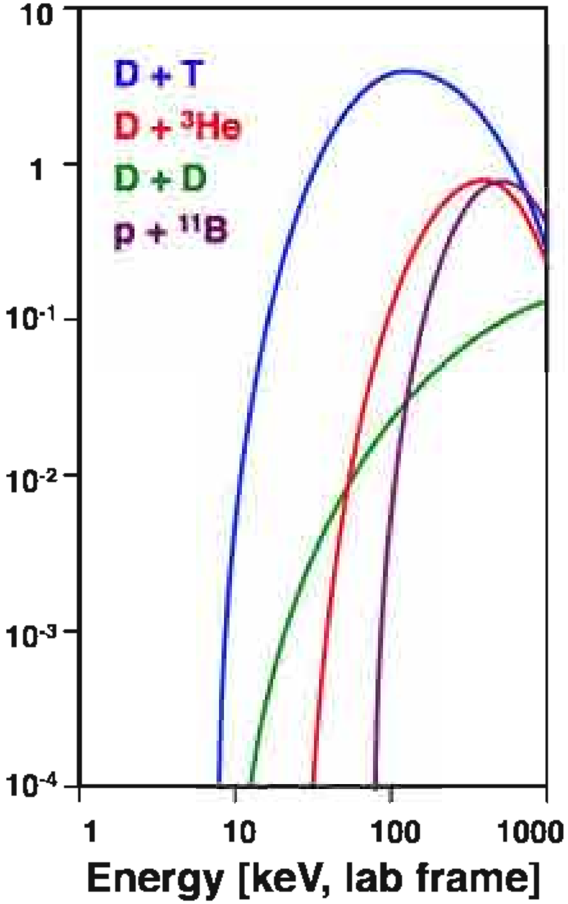


Ion species at same temperature

T. H. Rider, *Phys. Plasmas* 4:1039 (1997) and Ph.D. thesis, MIT (1995)

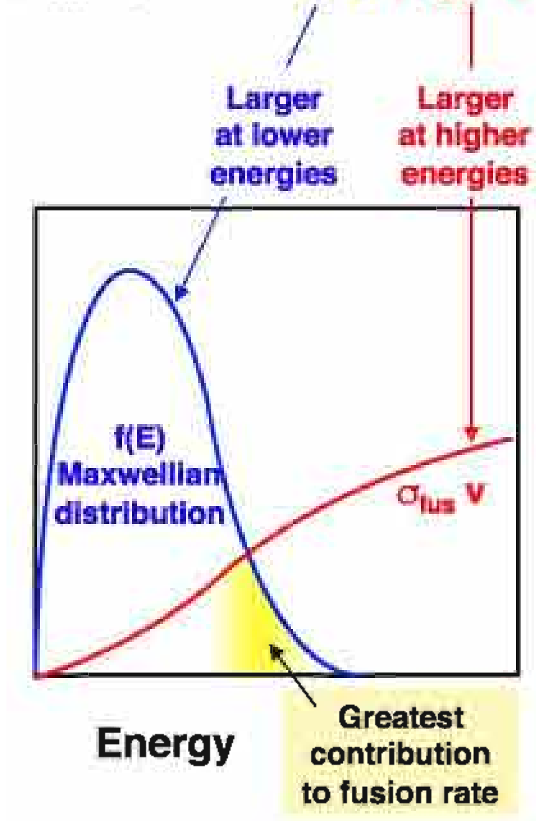
Cross Sections for Major Fusion Reactions

σ_{fus} [barns] for major reactions

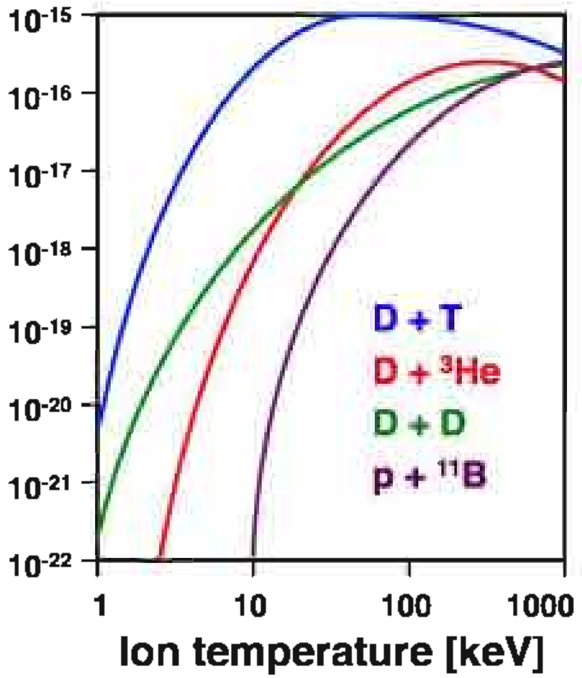


Reaction rate/volume $= \langle \sigma_{fus}\ v \rangle\ n_{i1}\ n_{i2}$

$$\langle \sigma_{fus}\ v \rangle = \int dE\ f(E)\ (\sigma_{fus}\ v)$$



$\langle \sigma_{fus}\ v \rangle$ [cm^3/sec] for major reactions



Electrons

You Can't Live Without Them

Space-charge-limited Brillouin density for ions without electrons:

$$\begin{bmatrix}\text{Confining field}\\ \text{energy density}\end{bmatrix} > \begin{bmatrix}\text{Ion rest}\\ \text{energy density}\end{bmatrix}$$

$$\rightarrow n_i < \frac{B^2/2\mu_o}{m_i c^2}$$

$\sim$ $5\text{x}10^{11}$ cm^{-3} for A~2 & B~20 T

Fusion power density limited to:

$$P_{fus} \sim 1\text{x}10^{-7}\, E_{fus,\ MeV} \langle \sigma v \rangle_{cm3/sec}\, n_{I\ cm\text{-}3}^{2}\ \text{W/m}^3$$

$\sim$ 100 W/m^3

Electrons must be present to reach useful fusion power densities.

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$$\sim\ 100\ \text{W/m}^3$$

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You Can't Live With Them

Ion-electron energy transfer rate (P_{ie}) if $T_i >> T_e$:

$$\frac{P_{ie}}{P_{fus}} \sim \frac{3\text{x}10^{-16}\quad Z^3\quad \ln\Lambda}{E_{fus,\,MeV}\langle\sigma v\rangle_{cm3/sec}\ A\ T_{i,\,keV}^{1/2}}\left[\frac{T_i}{T_e}\right]^{3/2}$$

~ 1 for $Z\sim1$, $\ln\Lambda\sim20$, $E_{fus}\sim18$ MeV
$\langle\sigma v\rangle\sim2\text{x}10^{-16}$ cm^3/sec,
$T_i/T_e\sim5$, $A\sim2$, $T_i\sim100$ keV

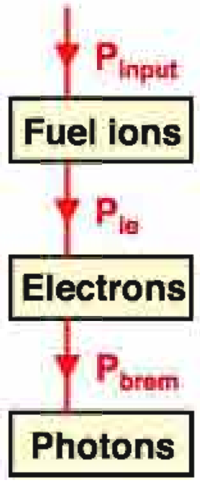
$P_{fus}>>P_{Input}$, so $P_{ie}>>P_{Input}$

Thus T_e must be $\sim T_i$ in equilibrium.

There are Z electrons for every ion, so electrons soak up ~Z/(Z+1) of the input energy without directly contributing to the fusion process.

Actually it's worse—see next slide...

Electrons Lose Energy via Bremsstrahlung Radiation



Electrons Lose Energy via Bremsstrahlung Radiation

If photons are confined

Photon vs. ion energy densities for equilibrium ($T_{photons} \approx T_i = T$):

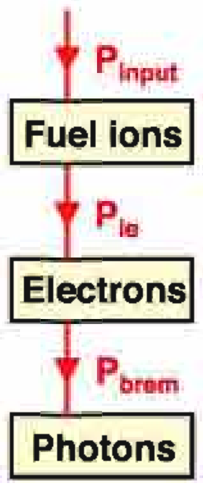
$$\frac{E_{photons}}{E_{ions}} \approx \frac{8\,\sigma_{SB}\,T^3}{3\,c\,k_B\,n_I}$$

Maximum achievable temperature before radiation soaks up most of the input energy ($E_{photons} > E_{ions}$):

$$T_{keV} \approx 2.6\text{x}10^{-8}\;n_{I,\,cm\text{-}3}^{1/3}$$

Just ~10 keV even for a stellar core ($n_i \sim 10^{26}$ cm^{-3})

Photons must be allowed to escape in order to reach useful ion temperatures at attainable densities (& thus useful power densities)



P_{input}

Fuel ions

P_{ie}

Electrons

P_{brem}

Photons

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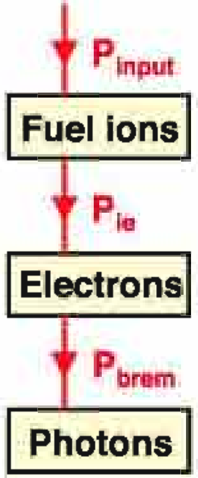

P_{input}

Fuel ions

P_{ie}

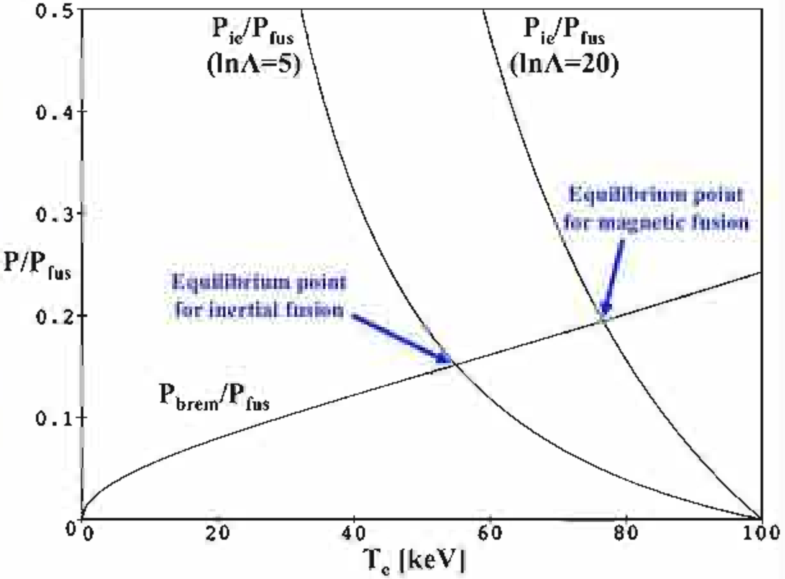
Electrons

P_{brem}

Photons

If photons escape

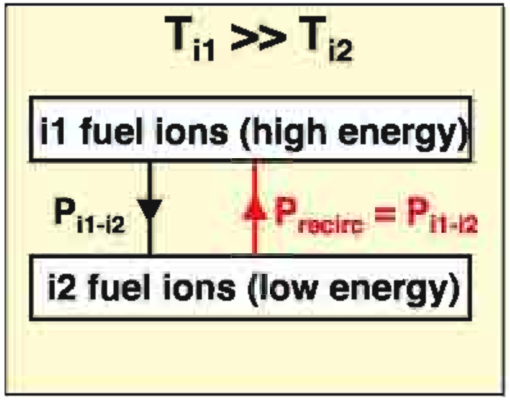
E.g.: 1:1 D+^{3}He with T_I=100 keV



Minimum P_{brem}/P_{fus} (magnetic)

D+T	0.007	Feasible
D+^{3}He (no D+D)	0.19	
D+D w/ T/^{3}He burnup	0.059	
D+D no T/^{3}He burnup	0.35	
p+^{11}B	1.19	Ouch
^{3}He+^{3}He	1.39	
p+^{6}Li	4.81	

Required Power to Maintain a Nonequilibrium Plasma



$T_{i1} >> T_{i2}$

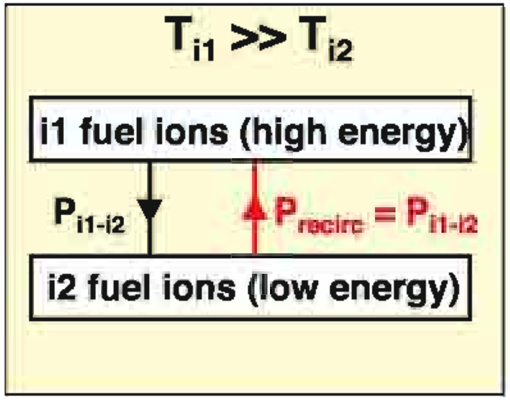
i1 fuel ions (high energy)

$P_{i1\text{-}i2}$

$P_{recirc} = P_{i1\text{-}i2}$

i2 fuel ions (low energy)

Required Power to Maintain a Nonequilibrium Plasma



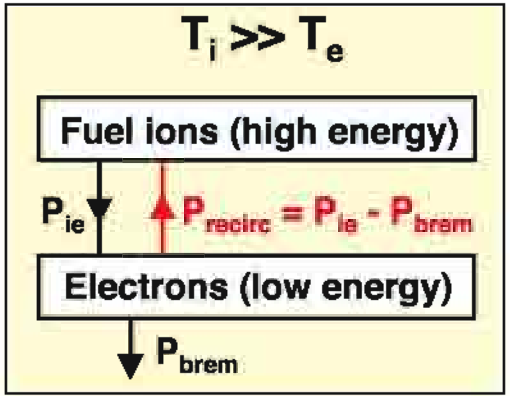
$T_{i1} >> T_{i2}$

i1 fuel ions (high energy)

$P_{i1\text{-}i2}$

$P_{recirc} = P_{i1\text{-}i2}$

i2 fuel ions (low energy)



$T_i >> T_e$

Fuel ions (high energy)

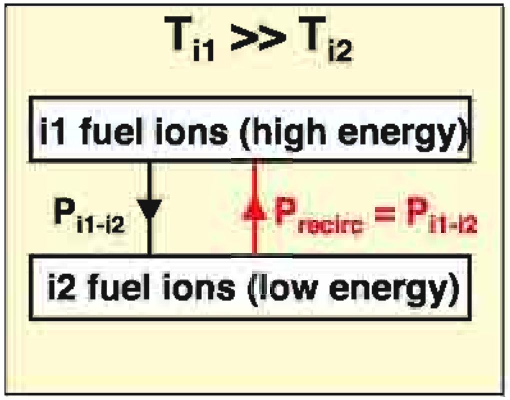
P_{ie}

$P_{recirc} = P_{ie} - P_{brem}$

Electrons (low energy)

P_{brem}

Required Power to Maintain a Nonequilibrium Plasma



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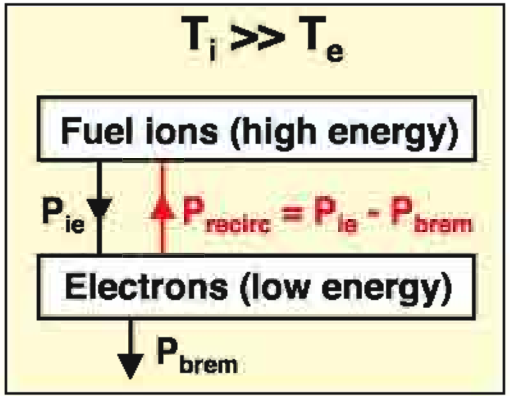

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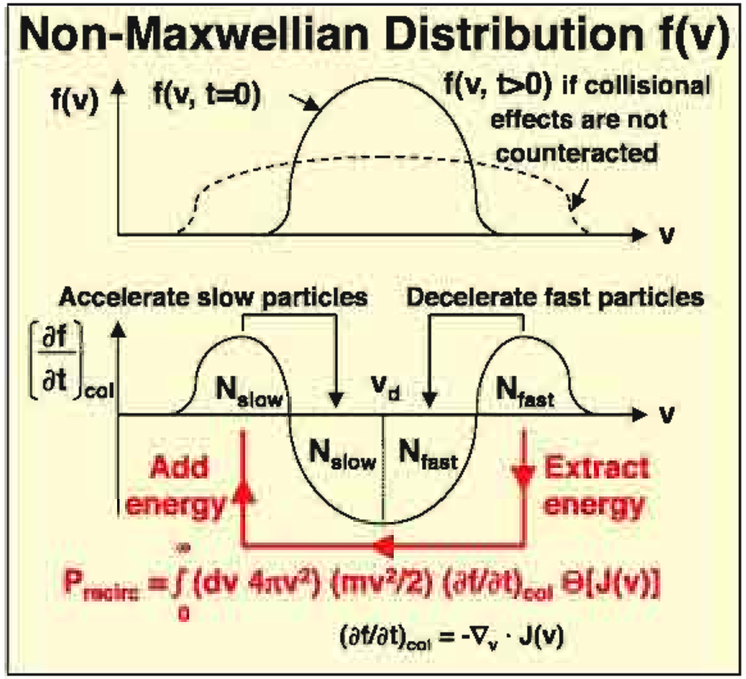

Non-Maxwellian Distribution f(v)

$$P_{recirc} = \int_0^{\infty} (dv\ 4\pi v^2)\ (mv^2/2)\ (\partial f/\partial t)_{col}\ \Theta[J(v)]$$

$$(\partial f/\partial t)_{col} = -\nabla_v \cdot J(v)$$

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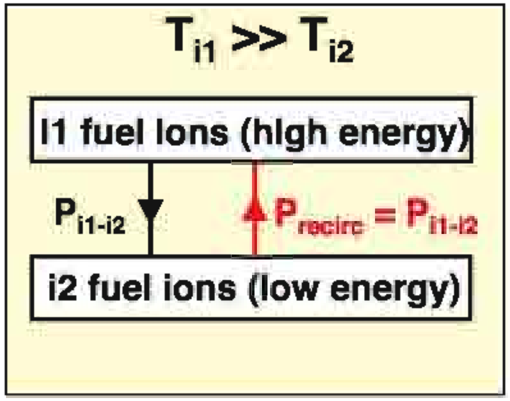

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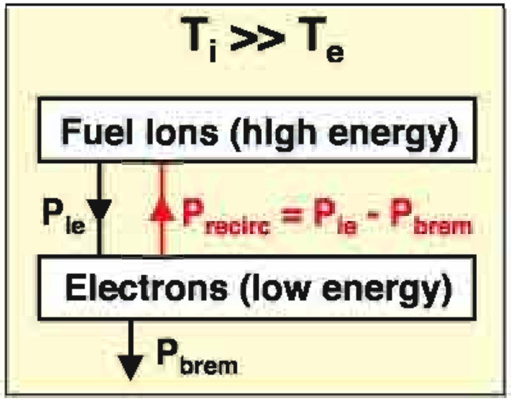

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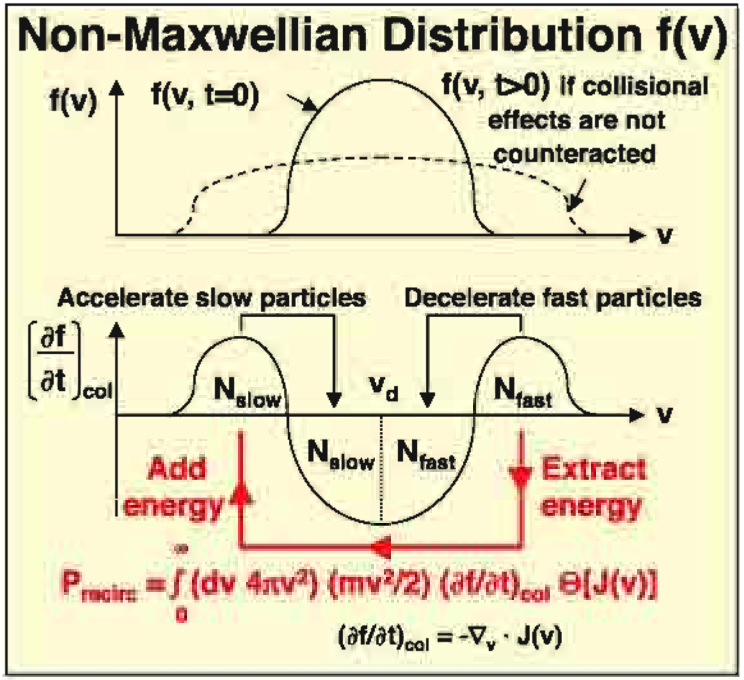

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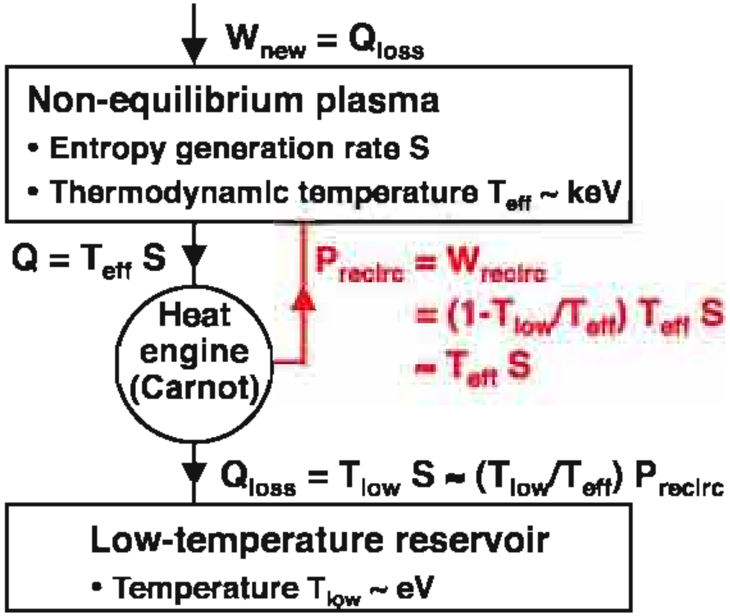
Idealized system for recirculating power to maintain a nonequilibrium plasma



$W_{new} = Q_{loss}$

Non-equilibrium plasma

- Entropy generation rate S
- Thermodynamic temperature T_{eff} ~ keV

$Q = T_{eff}\, S$

Heat engine (Carnot)

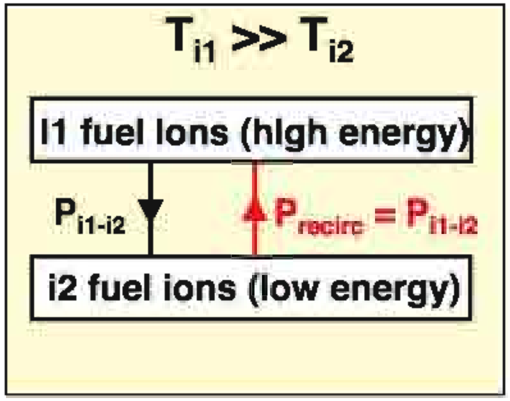
$$P_{recirc} = W_{recirc} = (1 - T_{low}/T_{eff})\, T_{eff}\, S \approx T_{eff}\, S$$

$Q_{loss} = T_{low}\, S \approx (T_{low}/T_{eff})\, P_{recirc}$

Low-temperature reservoir

- Temperature T_{low} ~ eV

Required Power to Maintain a Nonequilibrium Plasma



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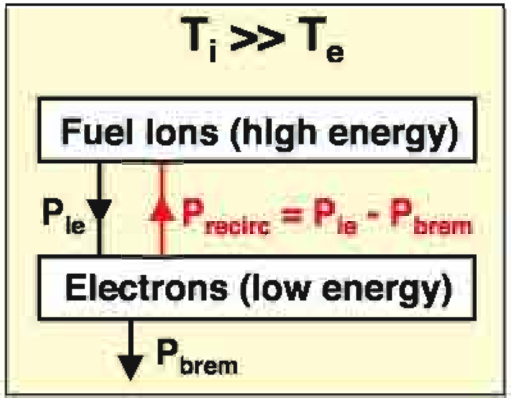

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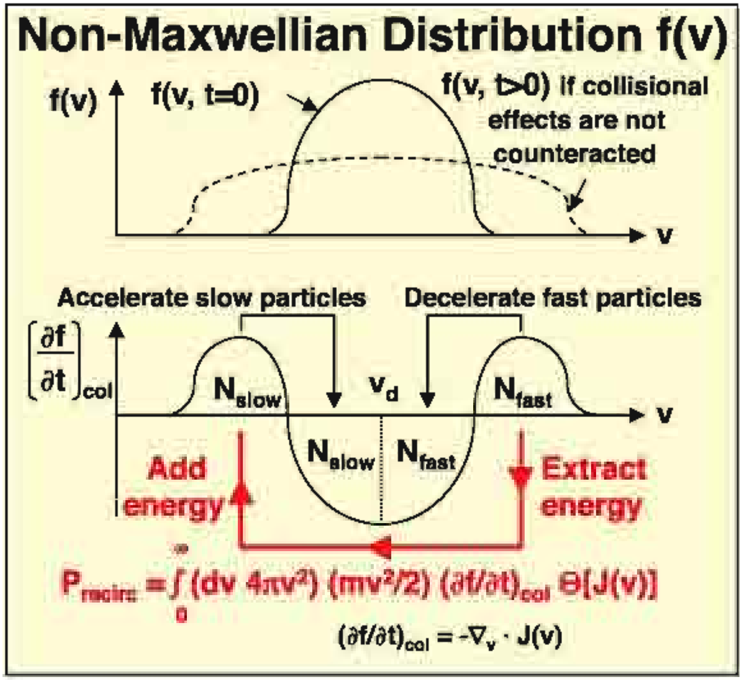

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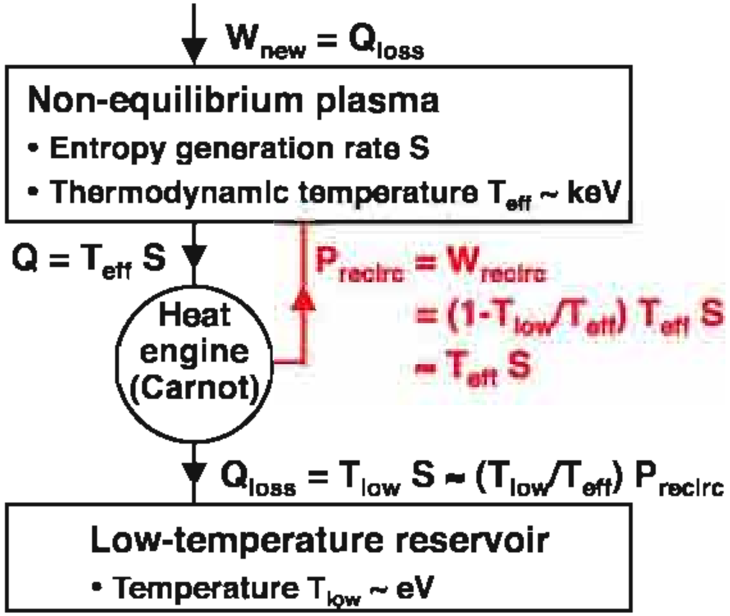

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$= (1 - T_{low}/T_{eff})\ T_{eff}\ S$
$\approx T_{eff}\ S$

$Q_{loss} = T_{low}\ S \approx (T_{low}/T_{eff})\ P_{recirc}$

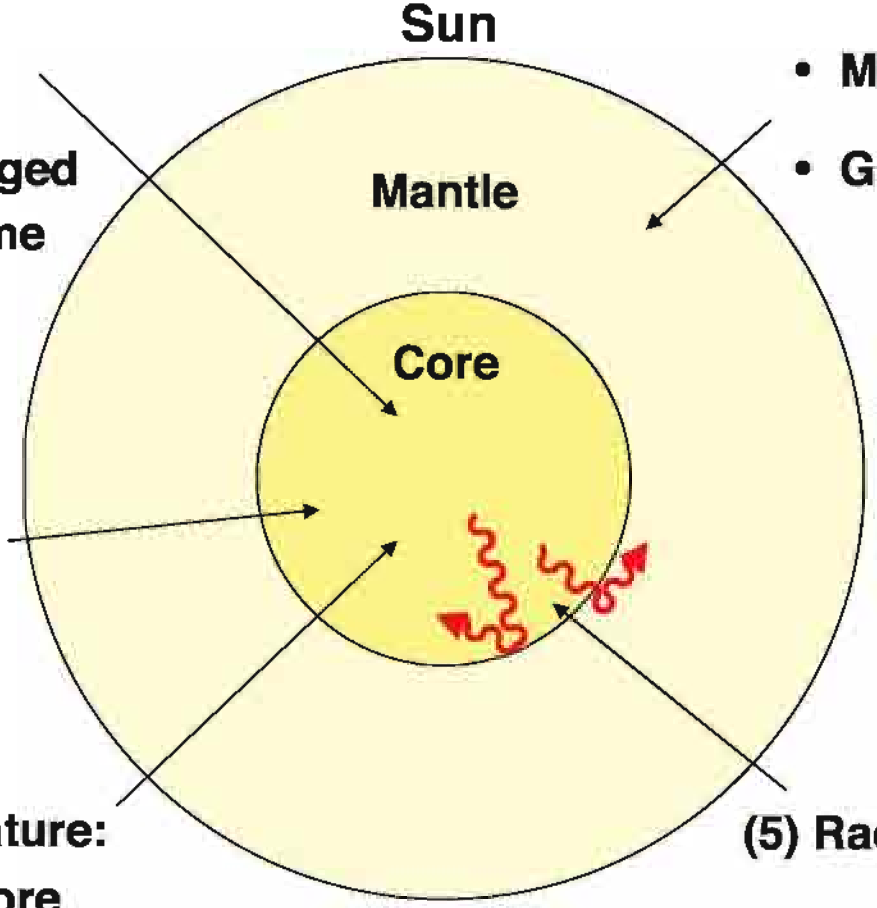
Low-temperature reservoir
- Temperature T_{low} ~ eV

- P_{recirc}/P_{fus} ~ 5-50 for most interesting cases
- Direct electric converters, resonant heating, etc. would lose too much power during recirculation
- Need novel approaches (e.g., nonlinear wave-particle interactions) that
  - Are >95% efficient
  - Recirculate the power *inside the plasma* without running P_{recirc}>>P_{fus} through external hardware
  - Are resistant to instabilities

T. H. Rider, *Phys. Plasmas* 4:1039 (1997) and Ph.D. thesis, MIT (1995), including App. E

Stellar Confinement of Fusion Plasma

Key Differences from Fusion Reactors



(1) Fusion power density:

- 83 W/m^3 in core
- 0.27 W/m^3 averaged over solar volume

(2) Fuel burnup time:

~10 billion years

(3) Ion temperature:

1.4 keV in core

(4) Particle confinement:

- Mantle confines core
- Gravity confines mantle

(5) Radiation losses:

- $T_{rad} \sim T_i$
- Loss $\propto T_{rad}^4$ but greatly impeded by mantle

H-Bomb Confinement of Fusion Plasma

RDS-6/Joe 4 (1953)

Shrimp/Castle Bravo (1954)

All information comes from unclassified sources such as: Atzeni & Meyer-Ter-Vehn 2004, *The Physics of Inertial Fusion.* Benedict et al 1981, *Nuclear Chemical Engineering.* Coster-Mullen 2012, *Atom Bombs.* Ford 2015, *Building the H Bomb.* Fortov 2016, *Extreme States of Matter.* Glasstone & Dolan 1977, *The Effects of Nuclear Weapons.* Goncharov 1996, *Physics–Uspekhi* 39:10:1033. Goncharov 1996, Thermonuclear Milestones, *Physics Today* 49:11:44. Goncharov & Riabev 2001, *Physics-Uspekhi* 44:1:71. Gsponer & Hurni 2009, *The Physical Principles of Thermonuclear Explosives.* Hansen 1988, *U.S. Nuclear Weapons.* Hansen 2007, *Swords of Armageddon.* Krehl 2009, *History of Shock Waves, Explosions and Impact.* Lindl 1998, *Inertial Confinement Fusion.* Morland 1981, *The Secret That Exploded.* Pondrom 2018, *The Soviet Atomic Project.* Reed 2015, *The Physics of the Manhattan Project.* Reed 2019, *The History and Science of the Manhattan Project.* Rhodes 1986, *The Making of the Atomic Bomb.* Rhodes 1995, *Dark Sun: The Making of the Hydrogen Bomb.* Serber 1992, *The Los Alamos Primer.* Smyth 1945, *Atomic Energy for Military Purposes.* Sublette 2019, nuclearweaponarchive.org. Wellerstein & Geist 2017, *Physics Today* 70:4:40. Winterberg 1981, *The Physical Principles of Thermonuclear Explosive Devices.* Winterberg 2010, *The Release of Thermonuclear Energy by Inertial Confinement.* Manhattan District History, https://ia802303.us.archive.org/26/items/ManhattanDistrictHistory.

H-Bomb Confinement of Fusion Plasma

RDS-6/Joe 4 (1953)

Shrimp/Castle Bravo (1954)

Key Differences from Fusion Reactors

(1) A fission bomb is a compact, self-powering source of input energy– not an option for fusion reactors.

(2) Fusion and fission reactions are complementary but together produce too much radioactivity for a reactor (fusion-fission hybrid reactors).

(3) Large size of bomb aids energy confinement, but makes the yield far too large for a reactor to contain.

(4) Large size of bomb also slows the expansion of the plasma, but again makes the yield far too large for a reactor.

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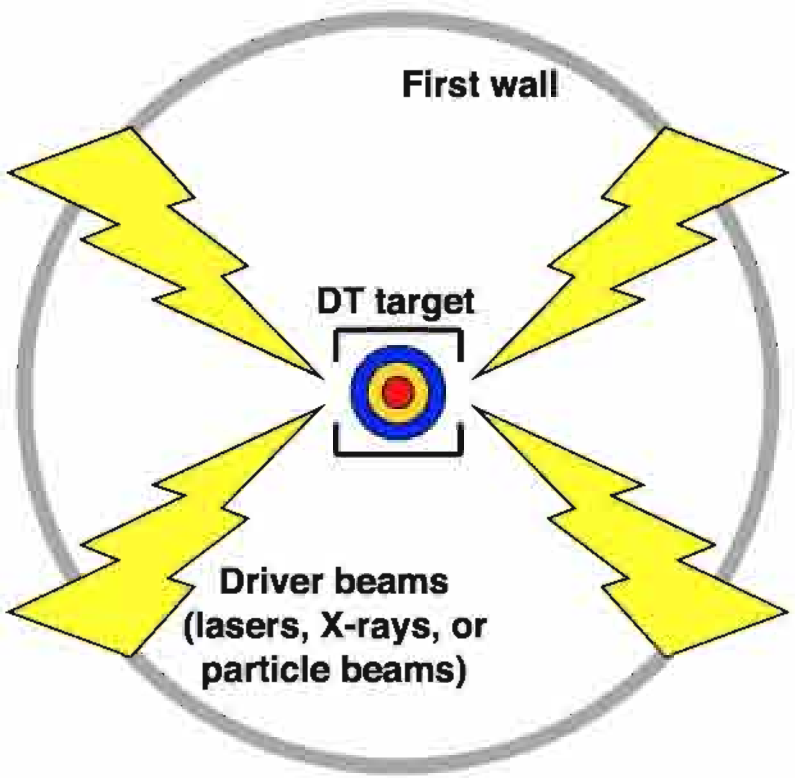
Inertial Confinement of Fusion Plasma

- Density ~ stellar core and temperature > stellar core, so pressure > stellar core.
- Without weight of an entire star to confine it, plasma expands rapidly, limited only by its own inertia.



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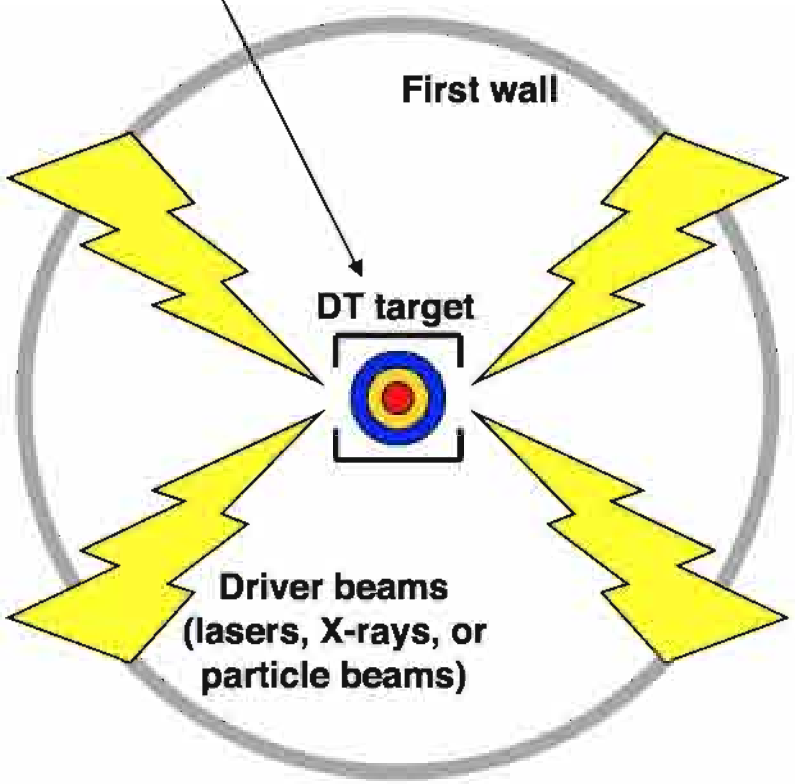
(1) Fuels other than DT would be even much more difficult.



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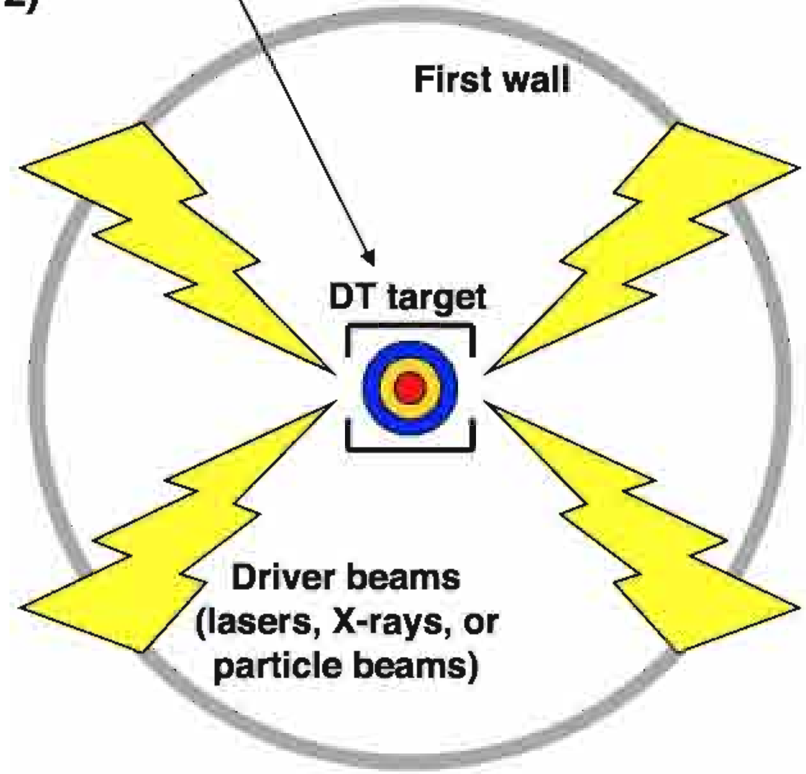

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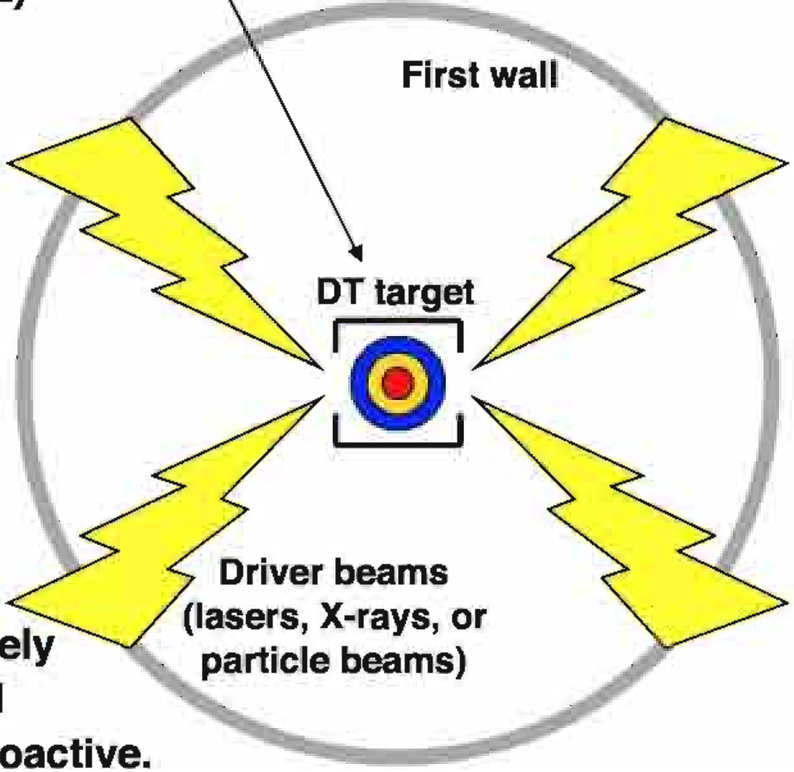

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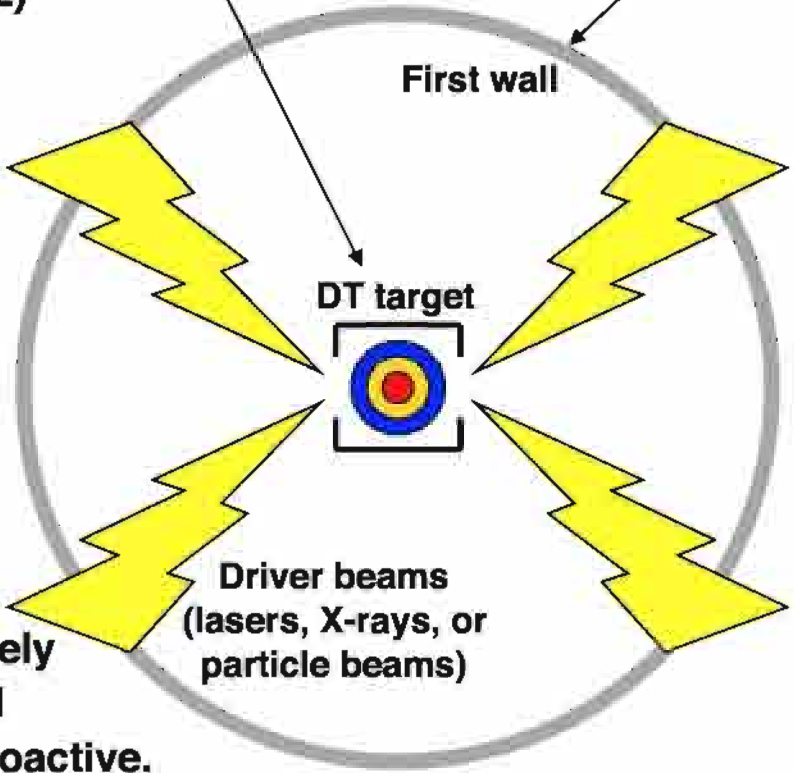

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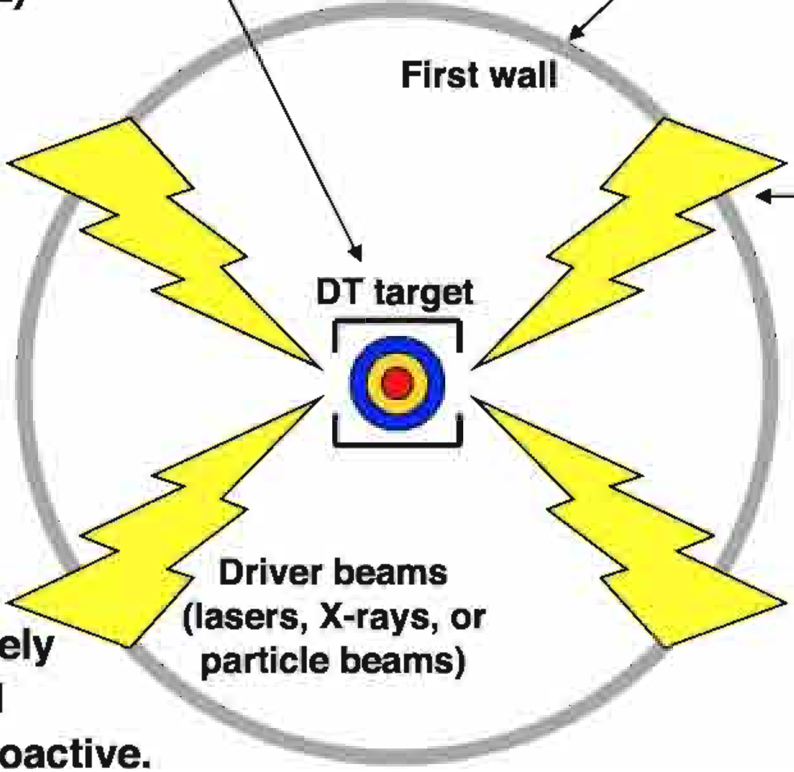

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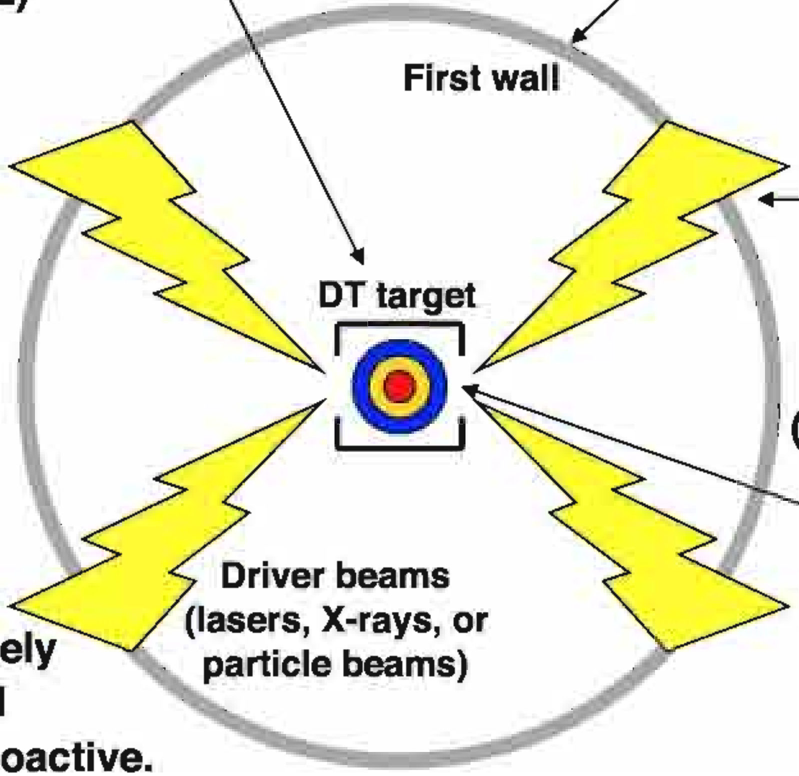

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(6) Lithium breeder material in walls must be converted into precisely fabricated DT targets and accurately positioned in chamber with throughput of several per second.

Inertial Confinement of Fusion Plasma

3.15 MJ fusion energy/shot (NIF, December 2022)

Gain compared to:

2.05 MJ laser UV (351 nm) energy	~1.5
4 MJ laser IR (1053 nm) energy	~0.79
8 MJ electrical energy with 50% efficient driver	~0.39
422 MJ laser electrical energy actually	~0.0075

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If fusion energy is converted to electrical energy at 1/3 thermal efficiency: ~1.05 MJ electrical output/shot

Gain compared to:

2.05 MJ laser UV (351 nm) energy	~0.51
4 MJ laser IR (1053 nm) energy	~0.26
8 MJ electrical energy with 50% efficient driver	~0.13
422 MJ laser electrical energy actually	~0.0025
~500 MJ to power NIF itself + >500 MJ net output	<0.001

For a power plant, gain would need to be increased ~1000x relative to current NIF performance.

Inertial Confinement of Fusion Plasma

3.15 MJ total fusion energy/shot (Dec. 2022) = 0.75 kg TNT equivalent.

Assume fusion energy converted to electrical energy at 1/3 thermal efficiency.

A power plant with 3 $\text{GW}_{\text{thermal}}$ or 1 $\text{GW}_{\text{electric}}$ would require:

1000 shots/second	at 3 MJ	or	0.72 kg TNT per shot
100 shots/second	at 30 MJ	or	7.2 kg TNT per shot
10 shots/second	at 300 MJ	or	72 kg TNT per shot
3 shots/second	at 1000 MJ	or	240 kg TNT per shot
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How large can the shots be without damaging any equipment
(or requiring impractical amounts of protection)?

NIF now: ~1 shot/day ~ 3 MJ total fusion energy/day
[lasers.llnl.gov/for-users/nif-target-shot-metrics]

Power plant: 3000 MJ total fusion energy/sec
~2.6×10^8 MJ total fusion energy/day

For a power plant, fusion energy output per day would
need to be increased ~10^8x relative to current NIF performance.

Inertial Confinement of Fusion Plasma

It has taken over 60 years of ICF development to achieve the current state of NIF [J.D. Lindl, 1998, *Inertial Confinement Fusion*, p. 16].

As of September 2012, NIF had cost over $5 billion [www.nytimes.com/2012/09/30/science/fusion-project-faces-a-frugal-congress.html], not counting earlier ICF machines and research.

What is the true total cost of NIF now? ~$10 billion? [current annual cost ~$0.624 billion, www.llnl.gov/news/national-ignition-facility-achieves-fusion-ignition]

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Compared to NIF, a power plant would need to increase:

- Gain by ~3 orders of magnitude AND
- Fusion energy output per day by ~8 orders of magnitude

How much would such a power plant cost?

How complex would such a power plant be?

How many more decades would be required to achieve that goal?

Why would electric utility companies buy many ICF power plants like that instead of cheaper, simpler, more readily available renewable, fission, or fossil fuel plants?