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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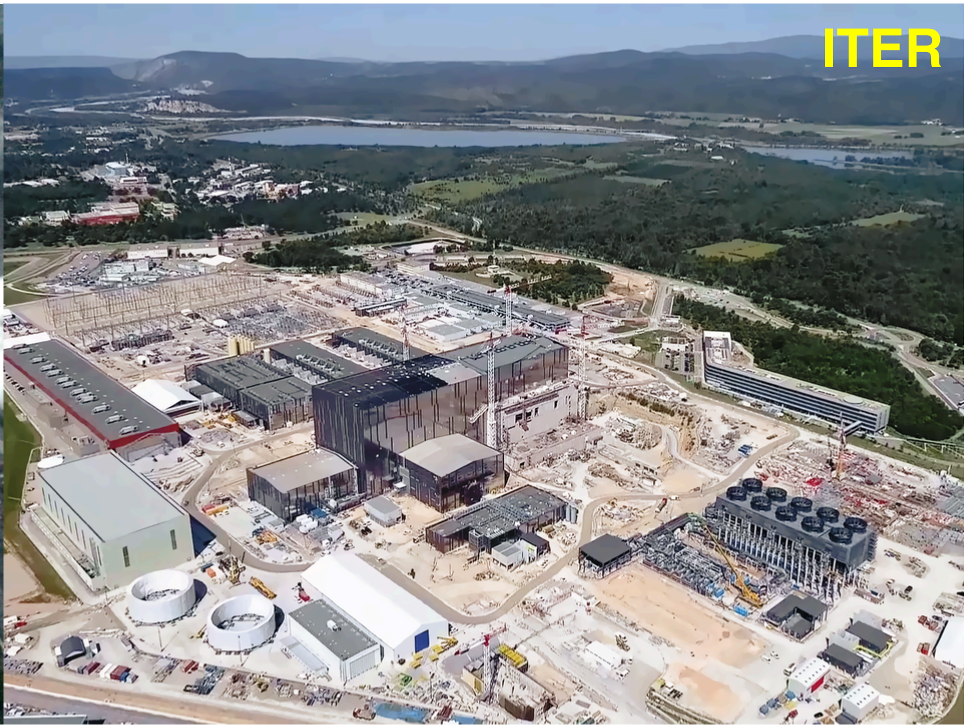

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- Still decades in the future after over 90 years of work

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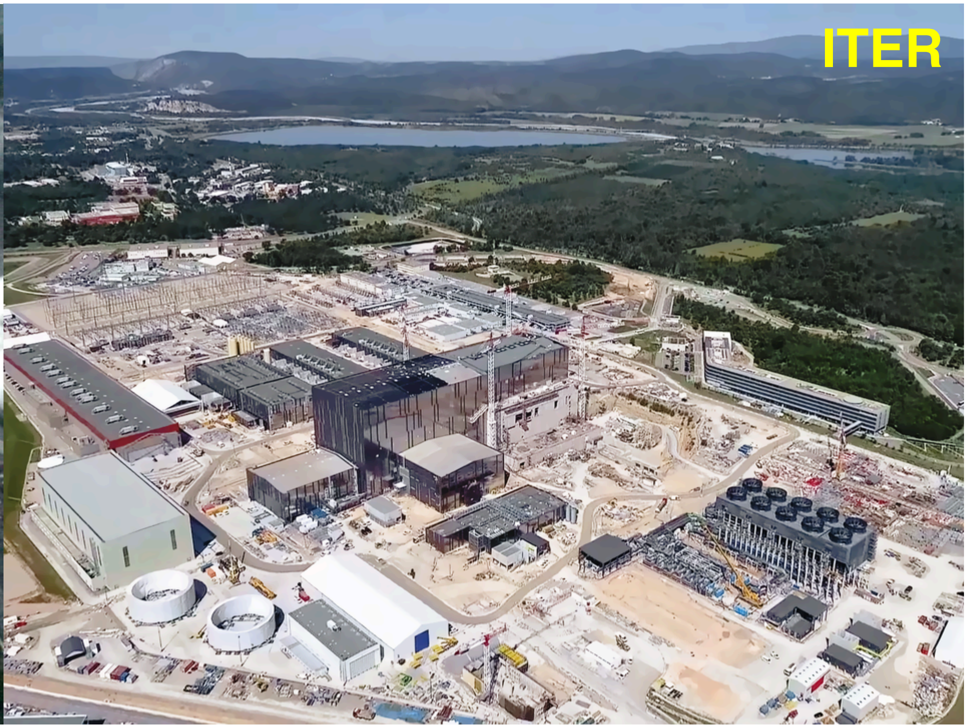

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➔ We will try to "rederive" nuclear power from first principles, looking for better approaches at each step along the way.

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?

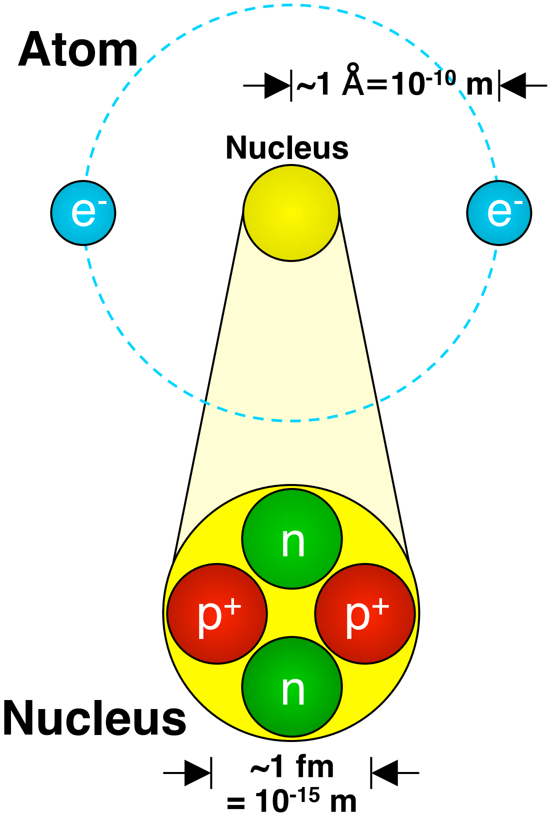
Nuclear vs. Chemical Energy

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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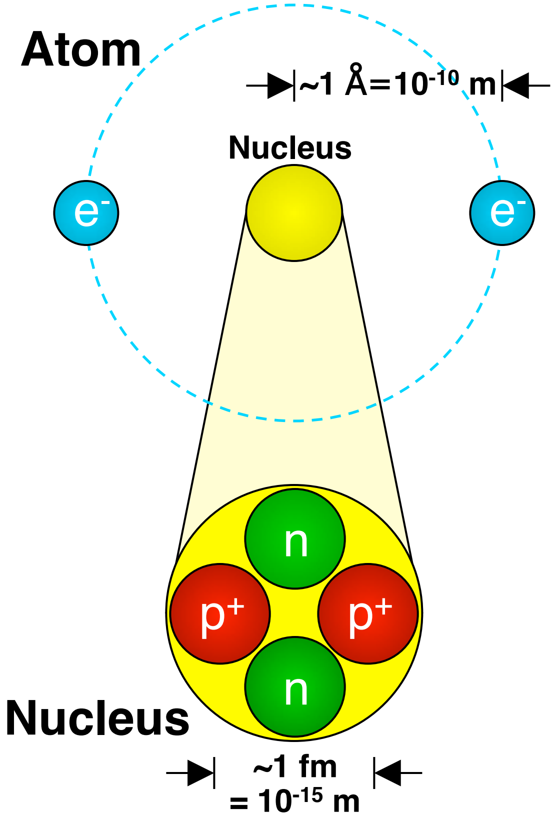

From Heisenberg uncertainty principle:

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

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

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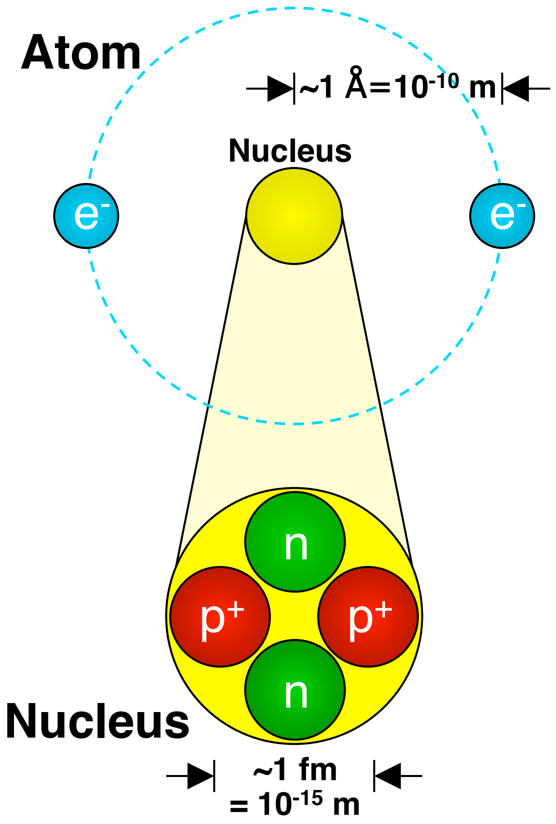

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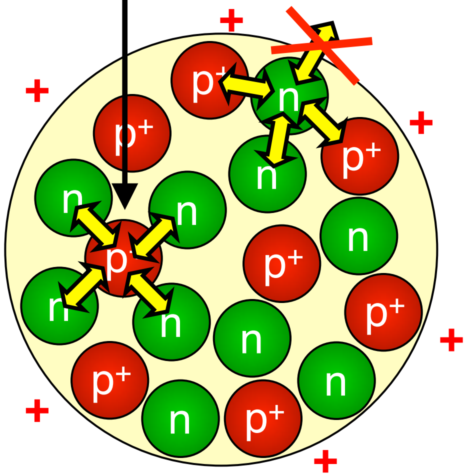
- Nuclear processes rearrange protons & neutrons and release ~10^5-10^6 more energy than chemical reactions, which rearrange atomic electrons (MeV vs. eV)
- A nuclear particle has enough energy to break ~10^5-10^6 chemical bonds
  - Can damage reactor components, depending on particle type & component 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 ≥ 15

Radius ~ $A^{1/3}$

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

Volume ~ A

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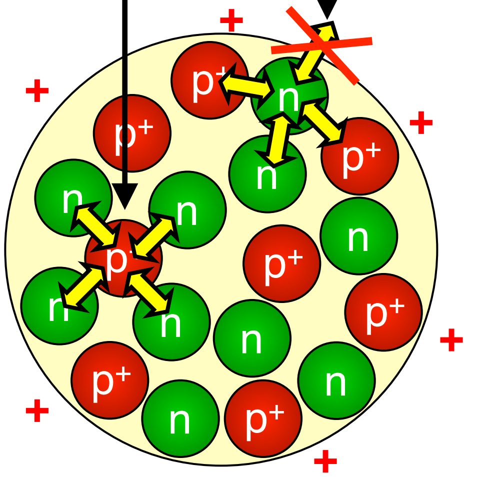

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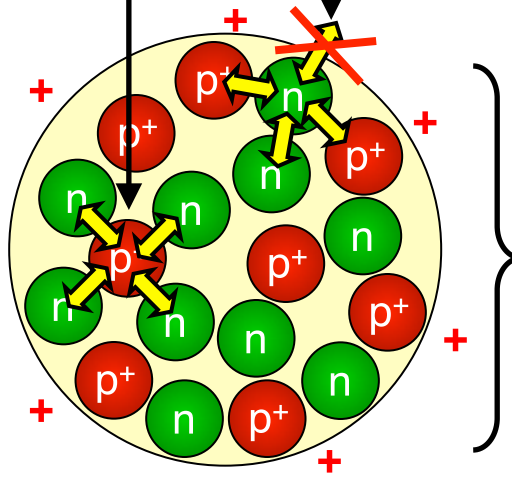
Coulomb repulsion among protons (favors N >> Z)



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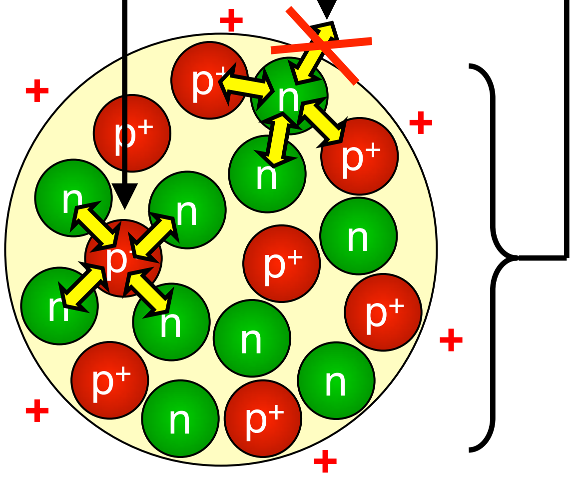

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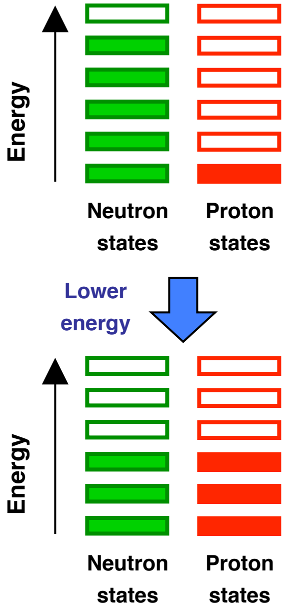
Energy cost of not filling neutron and proton states to same level (favors N ≈ Z)



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

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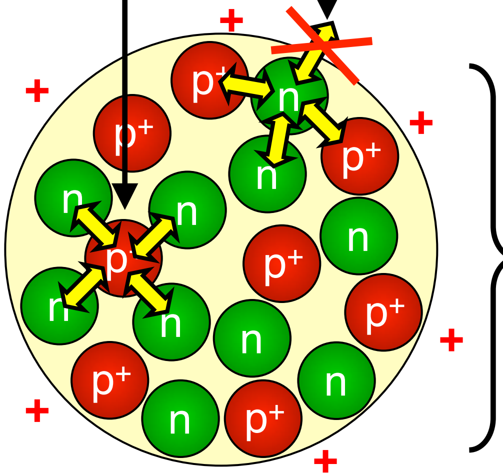

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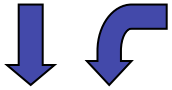

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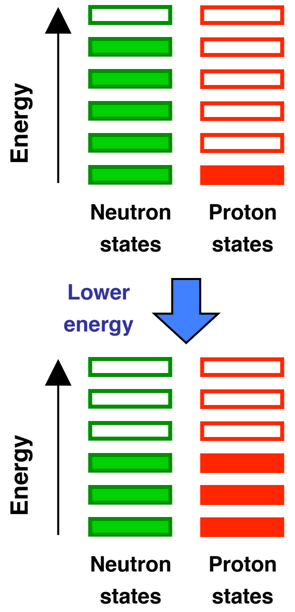
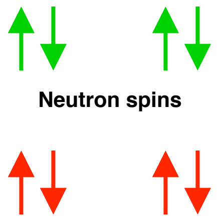


Nuclei are happiest when each nucleon is part of a pair with opposite spins



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if N or Z is magic

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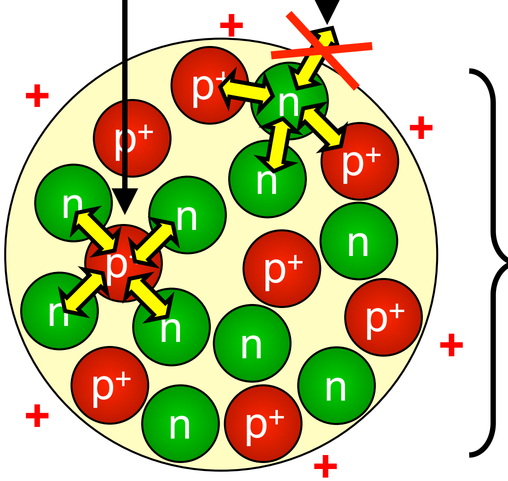

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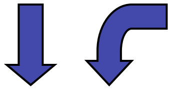

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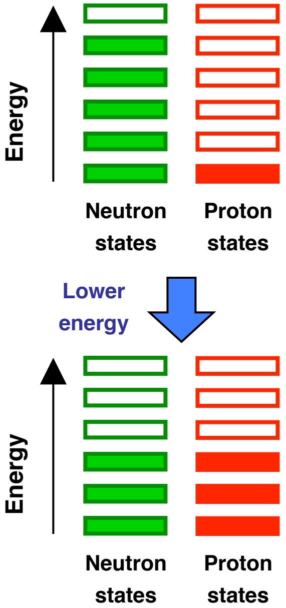

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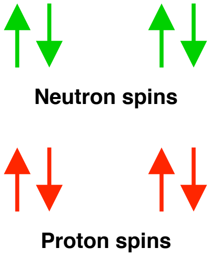
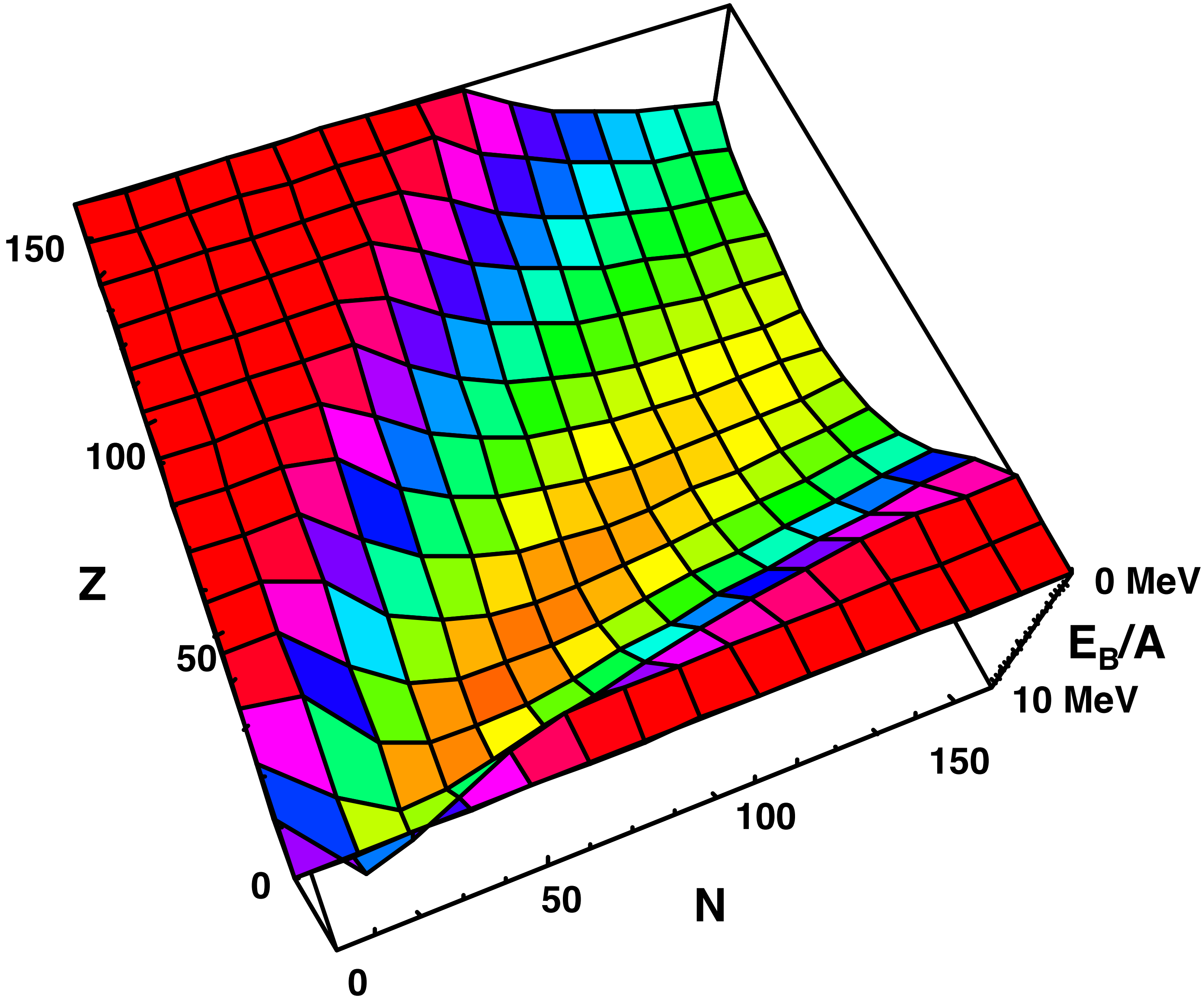


Bonus for filled nucleon energy shells at magic numbers of N and Z: 2, 8, 20, 28, 50, 82, 126, … (similar to atomic electron shells)

Binding Energy per Nucleon And Methods of Tapping It



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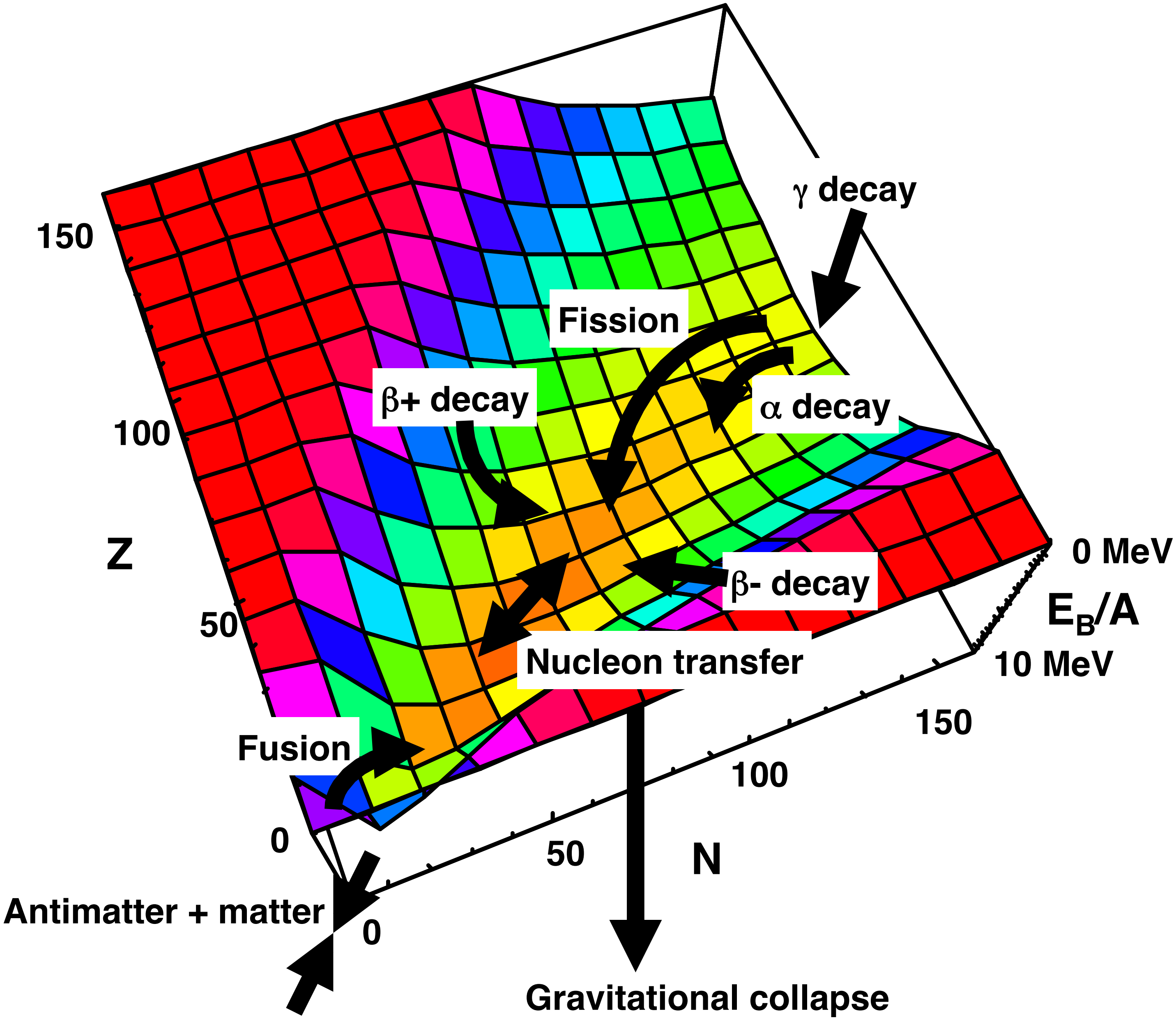

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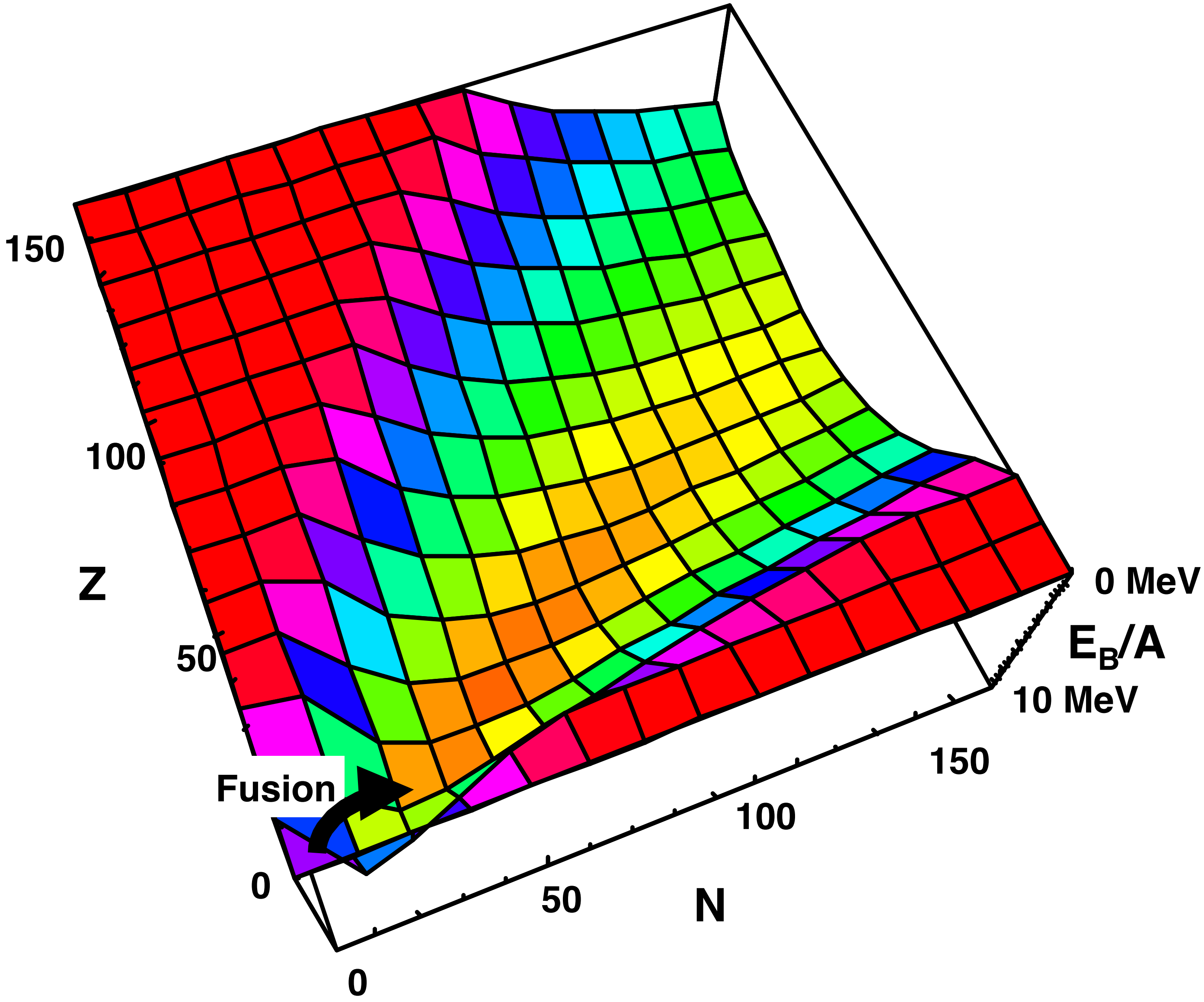
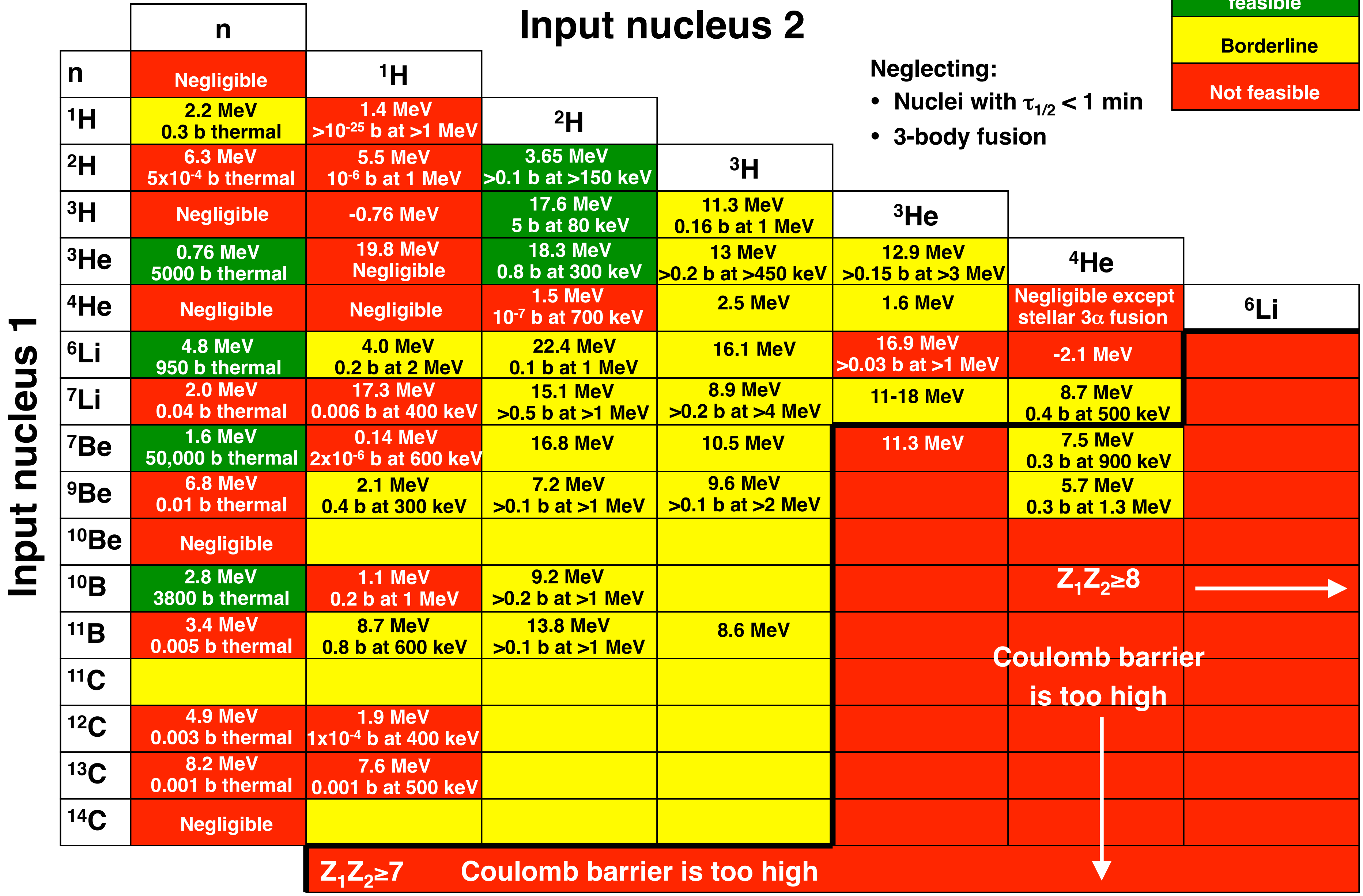


Possible Fusion Reactions

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

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^{-6} 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	🟨	🟨	🟨	🟥	🟥	🟥

$Z_1Z_2 \geq 8$ →

Coulomb barrier is too high

$Z_1Z_2 \geq 7$ Coulomb barrier is too high

Physical Factors in Fusion Cross Section (in barns)

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

σ_{fus}=

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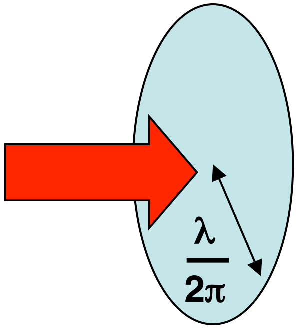
$$\sigma_{fus} = \frac{650}{A_{red}E_{CM}}$$

$$A_{red} \equiv \frac{A_1A_2}{(A_1+A_2)}$$

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



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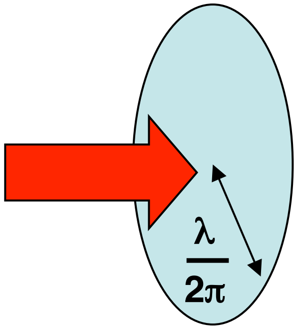
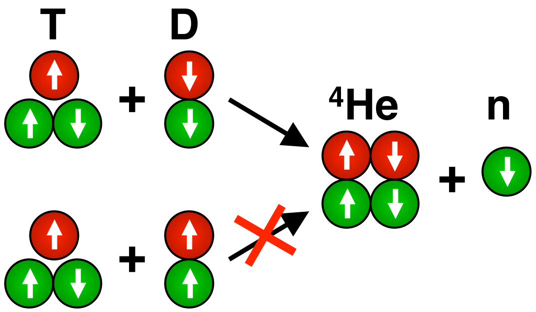


Input nuclei must have correct spins to fuse

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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$$A_{red} \equiv \frac{A_1A_2}{(A_1+A_2)}$$

Probability of tunneling through Coulomb barrier between nuclei

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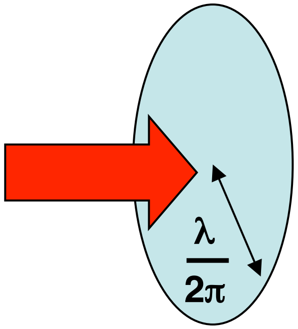

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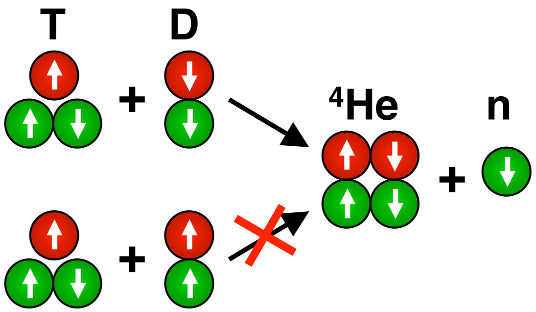

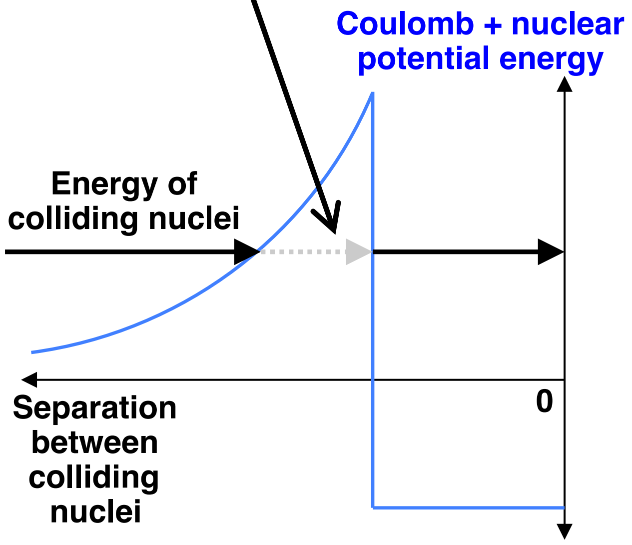

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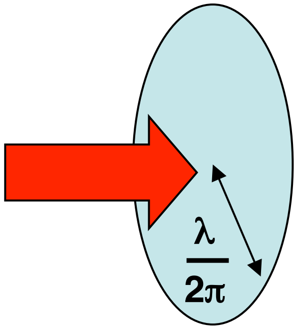

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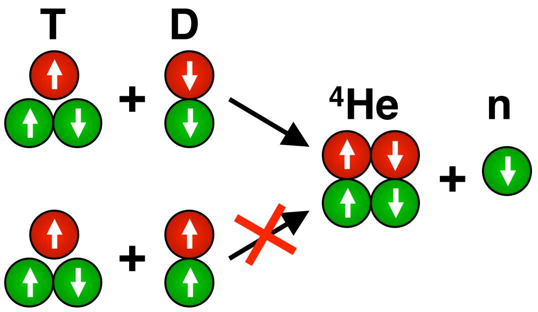

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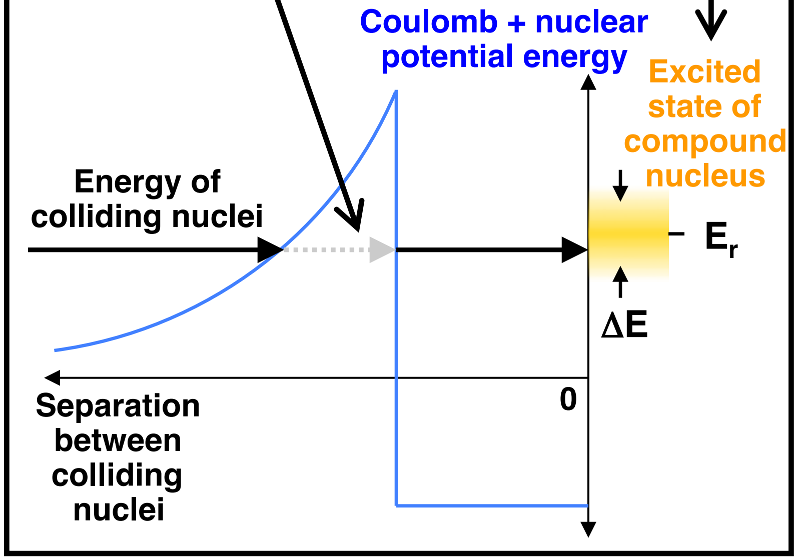
Collision energy E_{CM} must be within ~$\Delta E/2$ of excited state energy E_r of compound nucleus



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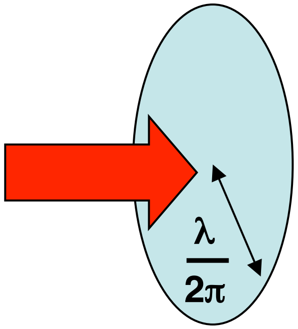

Are there any ways to improve or alter this factor other than its obvious dependence on A_{red} and E_{CM}?

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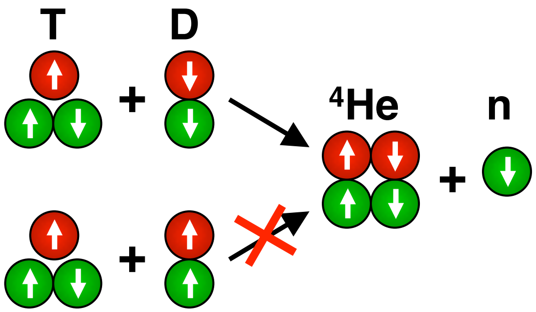
Input nuclei must have correct spins to fuse

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



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.
Kulsrud, Valeo, & Cowley 1986, *Nuclear Fusion* 26:1443 and *Phys. Fluids* 29:430.
Poelker et al 1994, *Phys. Rev. A* 50:2450. Redsun et al 1990, *Phys. Rev. A* 42:1293.
Zhang & Balescu 1988, *J. Plasma Physics* 40:199 & 215.

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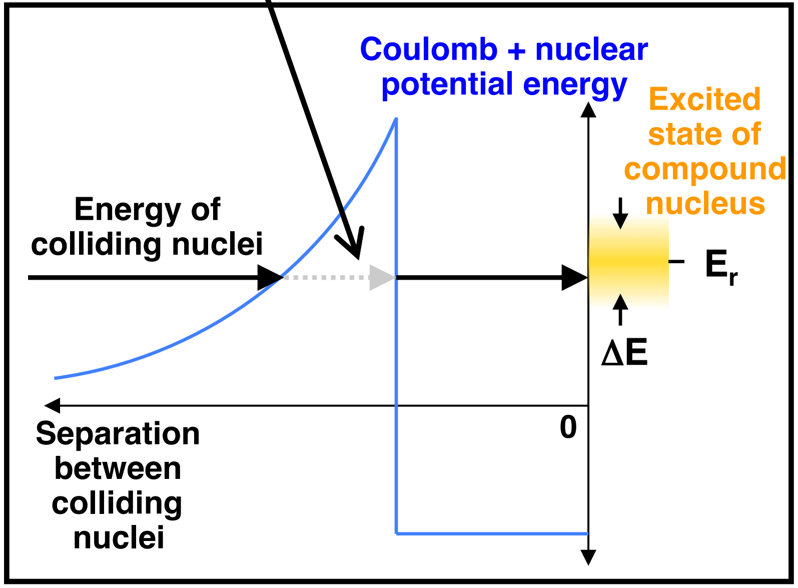
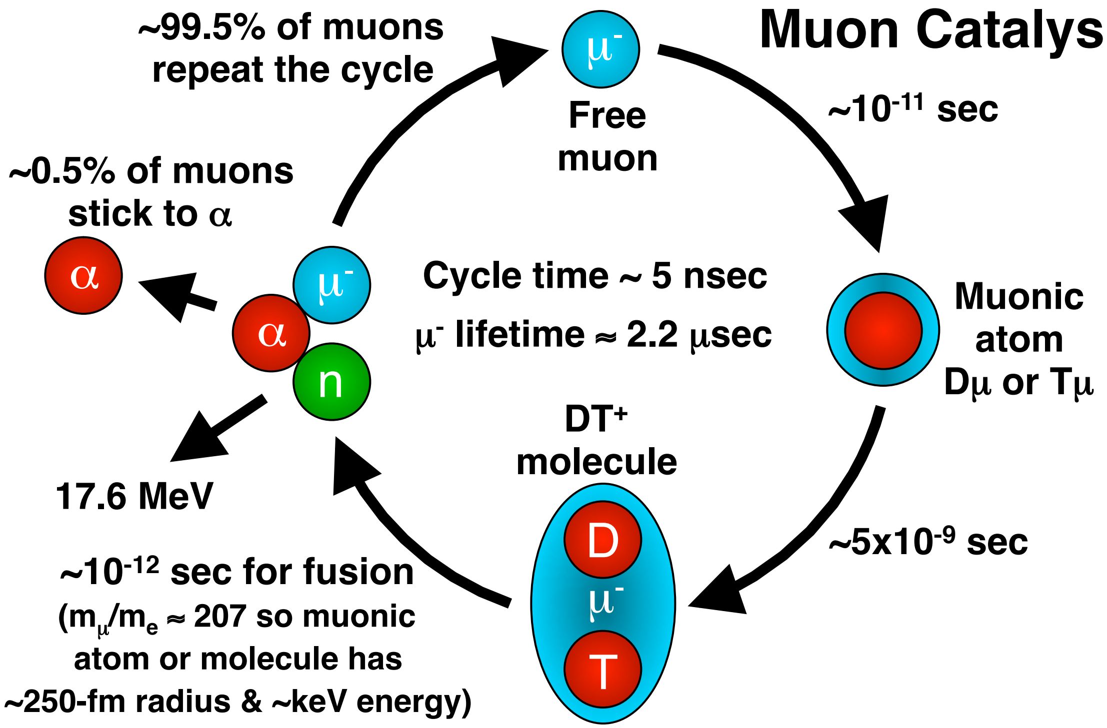
Probability of tunneling through Coulomb barrier between nuclei

Shave the outer edge of the Coulomb barrier



Shave the Outer Edge of the Coulomb Barrier

Muon Catalysis [1]



Free muon μ^-

~10^{-11} sec

Muonic atom $D\mu$ or $T\mu$

~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

~99.5% of muons repeat the cycle

Cycle time ~ 5 nsec

μ^- lifetime ≈ 2.2 μsec

---

[1] Brunelli & Leotta 1987, *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei*. Plenum Press.

[2] Fujiwara et al 2000, *Phys. Rev. Lett.* 85:1642--only decreases the time for the *first* cycle, not later ones.

[3] Morgan, Perkins, & Haney 1996, *Hyperfine Interactions* 102:503.

[4] Landis & Huizenga 1989, Report DOE/S-0073, www.osti.gov/servlets/purl/5144772.

[5] Yakovlev & Shalybkov 1987, *Sov. Astron. Lett.* 13:4:308. Ichimaru 1993, *Rev. Mod. Phys.* 65:255. Aliotta & Langanke 2022, *Frontiers in Physics* 10:942726.

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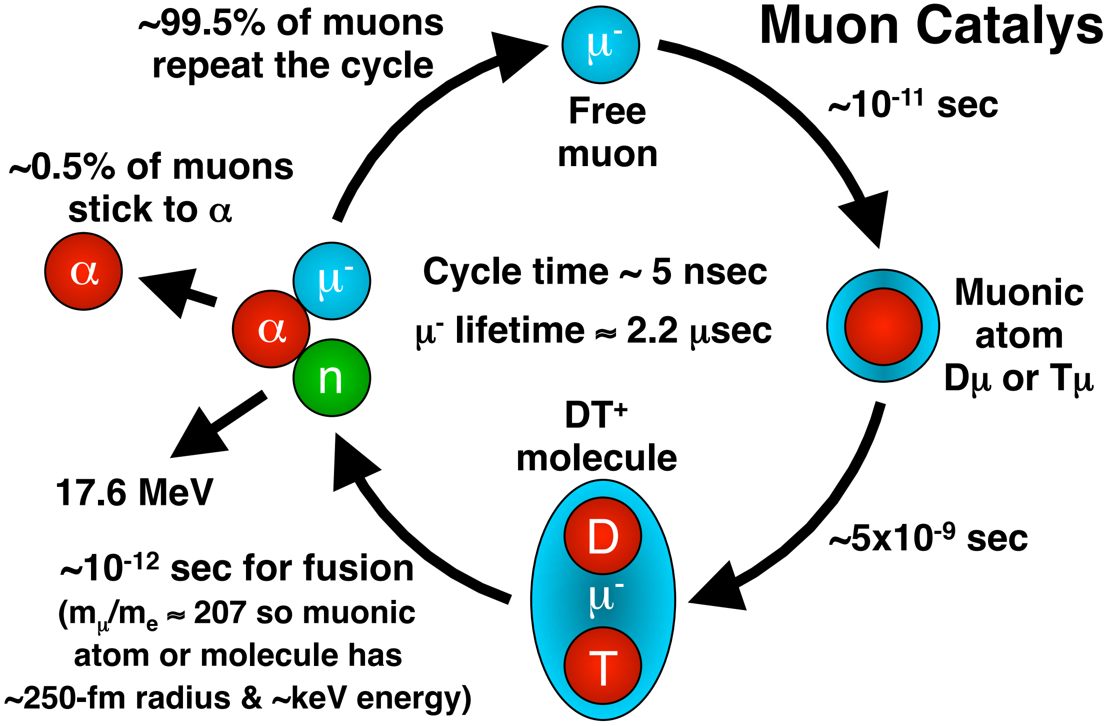

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Cycle time ~ 5 nsec

μ^- lifetime $\approx$ 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 ~$(0.5\%)^{-1} \approx$ 200 fusions before sticking to α

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

Need unsticking methods

Could then catalyze 2.2μs / 5ns
$\approx$ 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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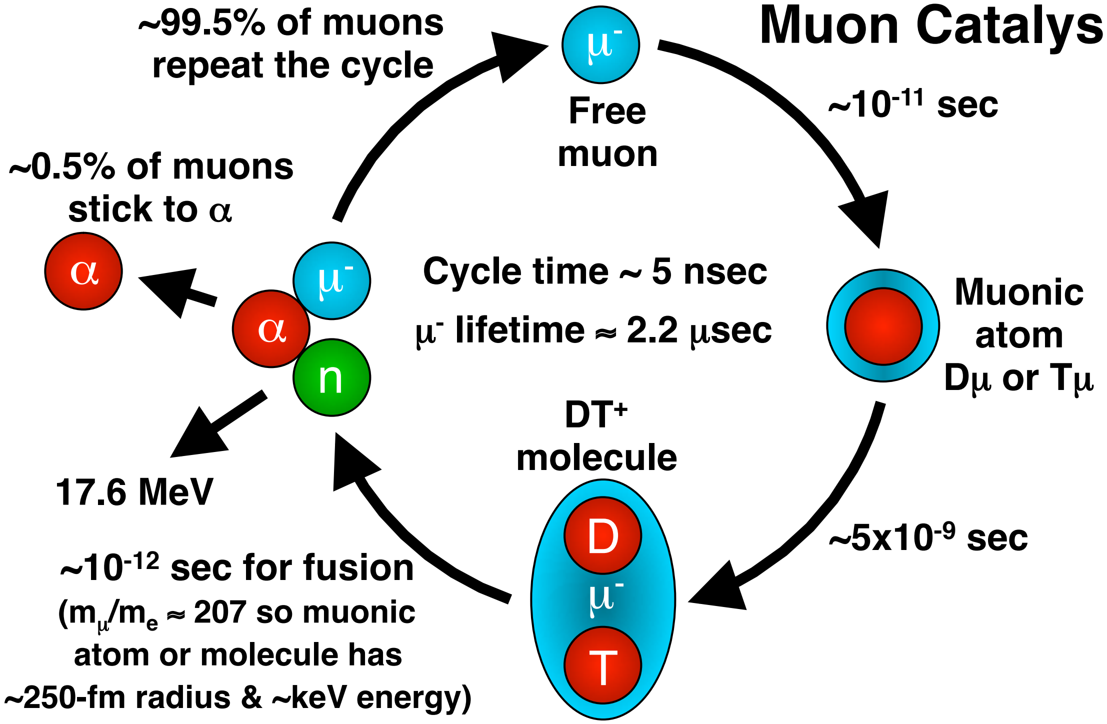

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D

μ^-

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17.6 MeV

α

μ^-

n

~0.5% of muons stick to α

α

Cycle time ~ 5 nsec

μ^- lifetime $\approx$ 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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↑ 2x increase

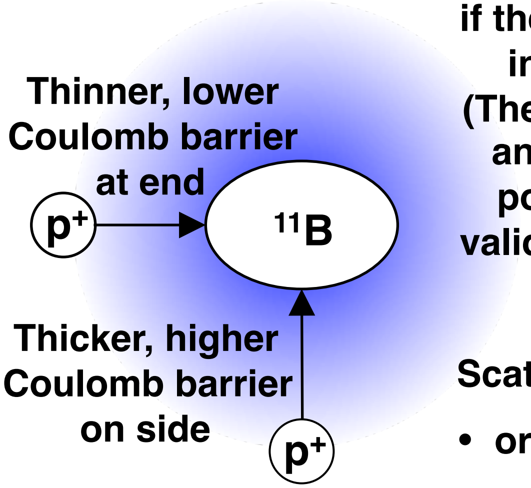
↑ 1.5

Probability of tunneling through Coulomb barrier between nuclei

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.)

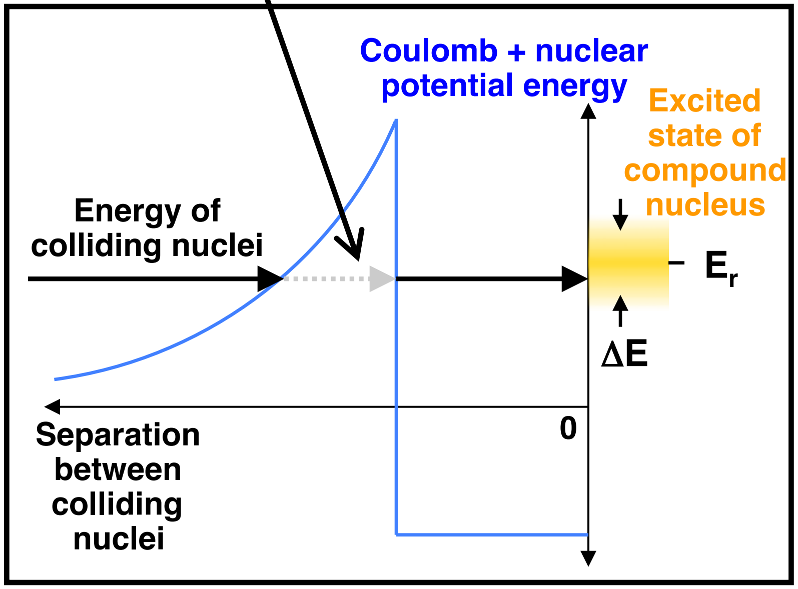


Scattering randomizes:

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

much faster than fusion

Shave the inner edge of the Coulomb barrier



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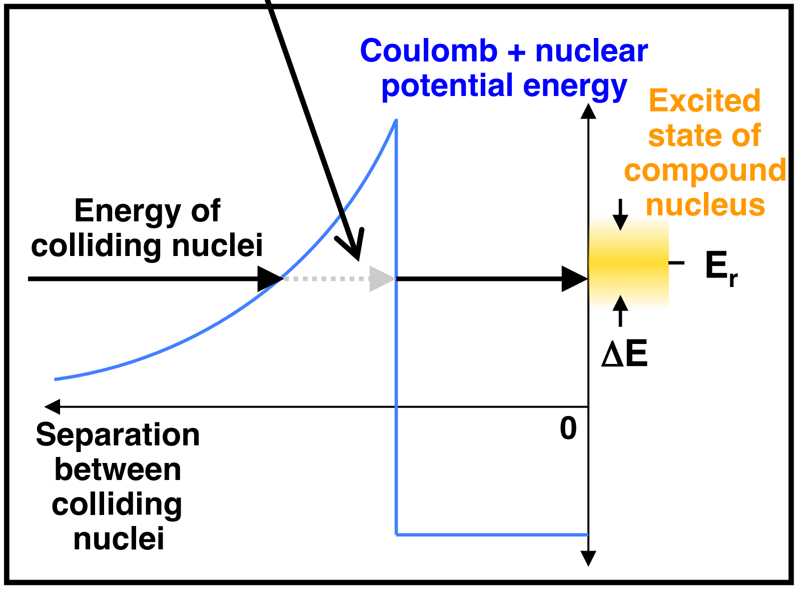

Are there other ways to beat the Coulomb barrier?

Physical Factors in Fusion Cross Section (in barns)

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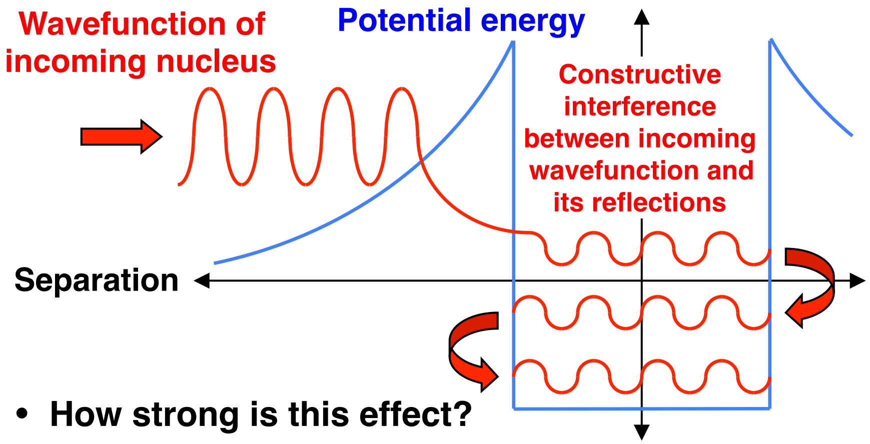
Probability of tunneling through Coulomb barrier between nuclei

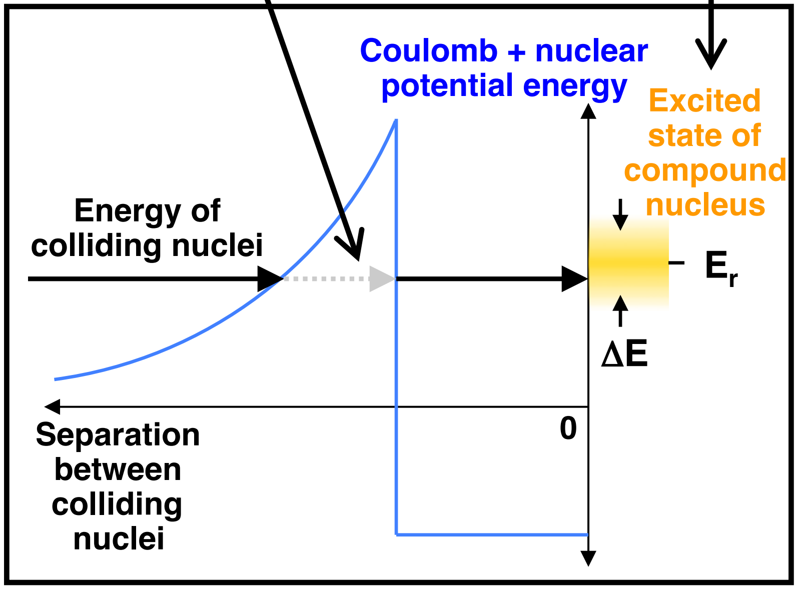
Collision energy E_{CM} must be within ~$\Delta E/2$ of excited state energy E_r of compound nucleus

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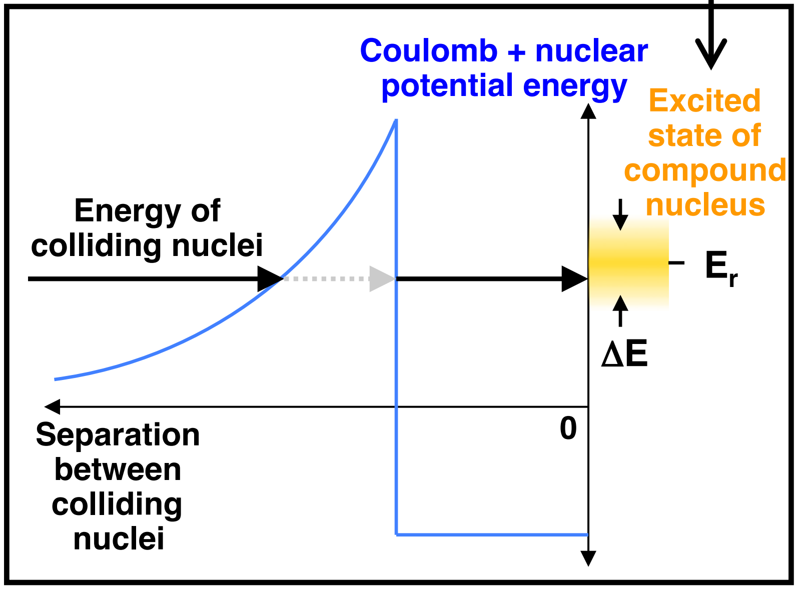
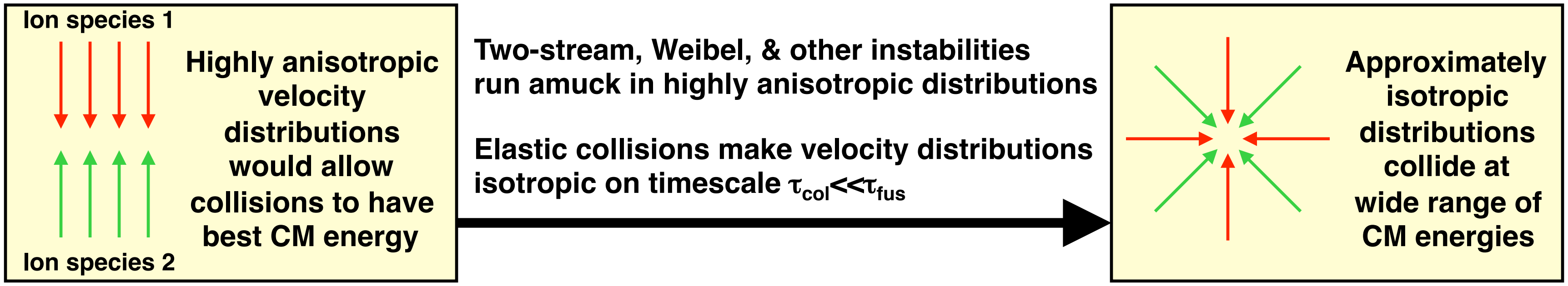
Are there any practical ways to create, heighten, broaden, or energy-shift a resonance of the compound nucleus?

- 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)

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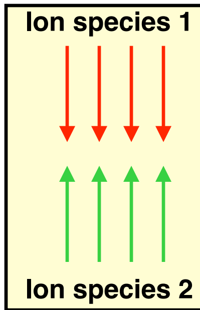

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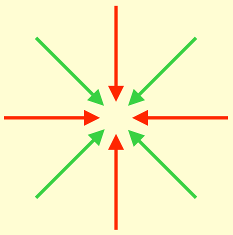

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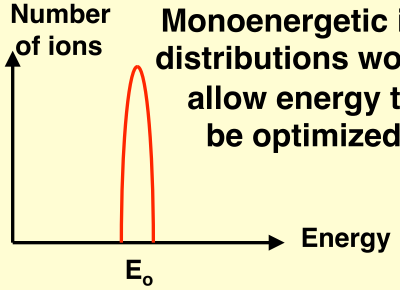
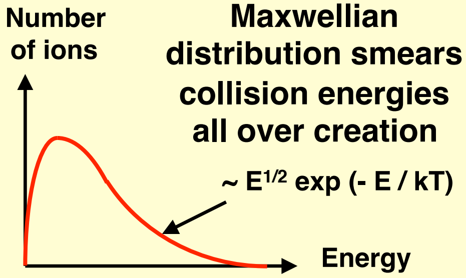


Monoenergetic ion distributions would allow energy to be optimized

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



Maxwellian distribution smears collision energies all over creation

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

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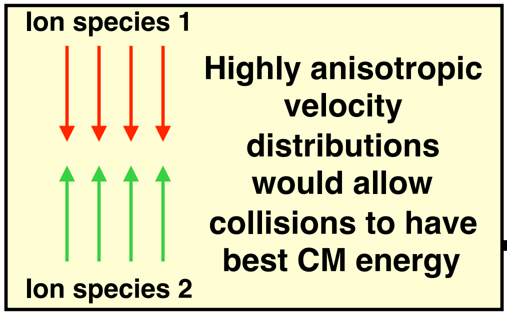

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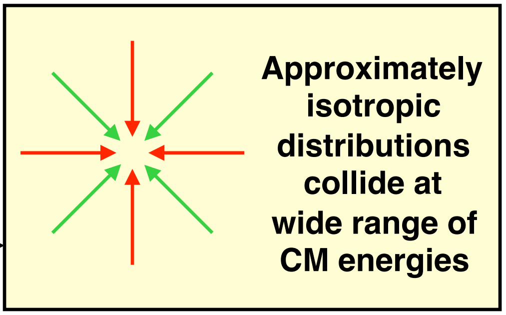

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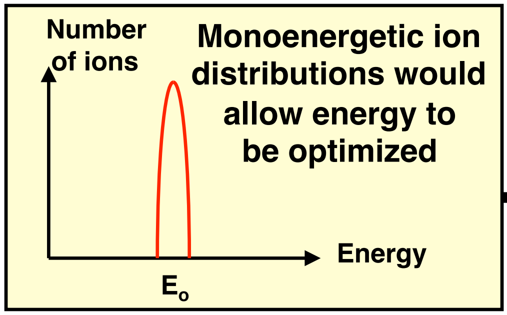

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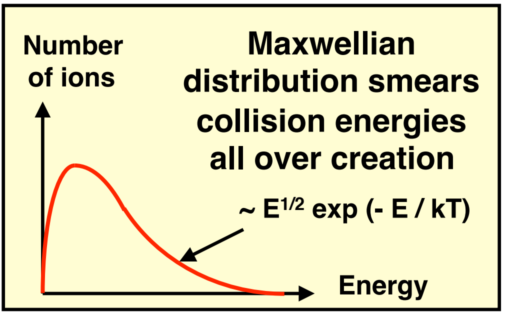

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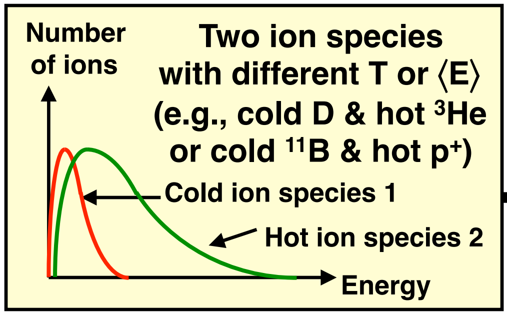
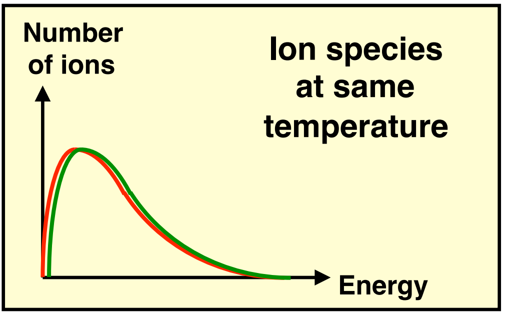


Two ion species with different T or ⟨E⟩ (e.g., cold D & hot ^{3}He or cold ^{11}B & hot p^{+})

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

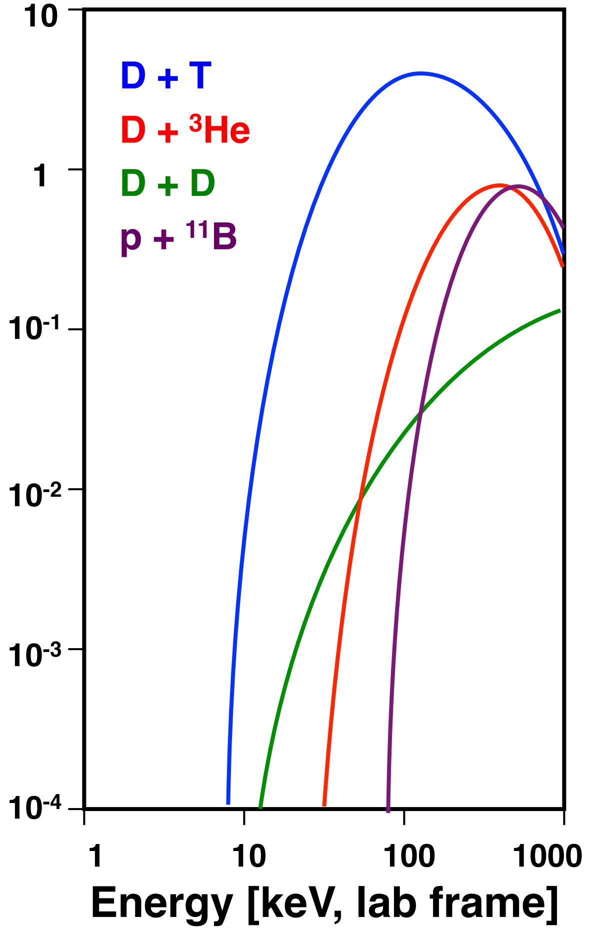


Ion species at same temperature

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

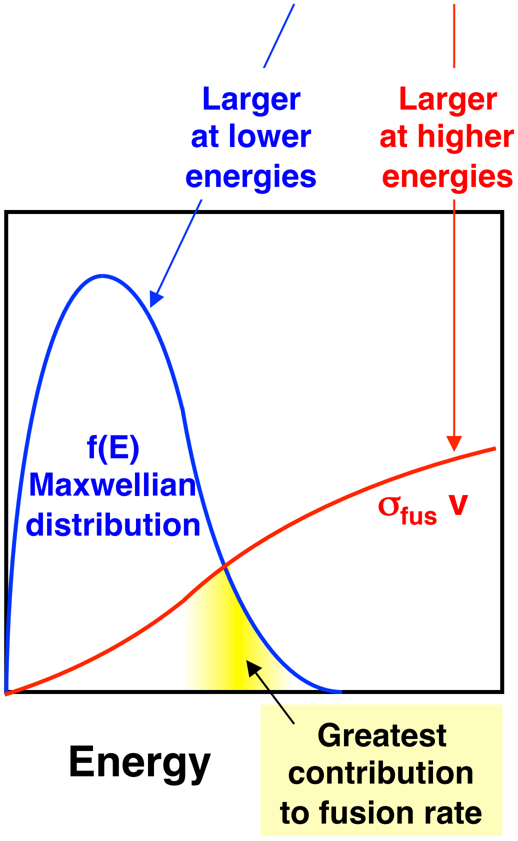
Cross Sections for Major Fusion Reactions

σ_{fus} [barns] for major reactions



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

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

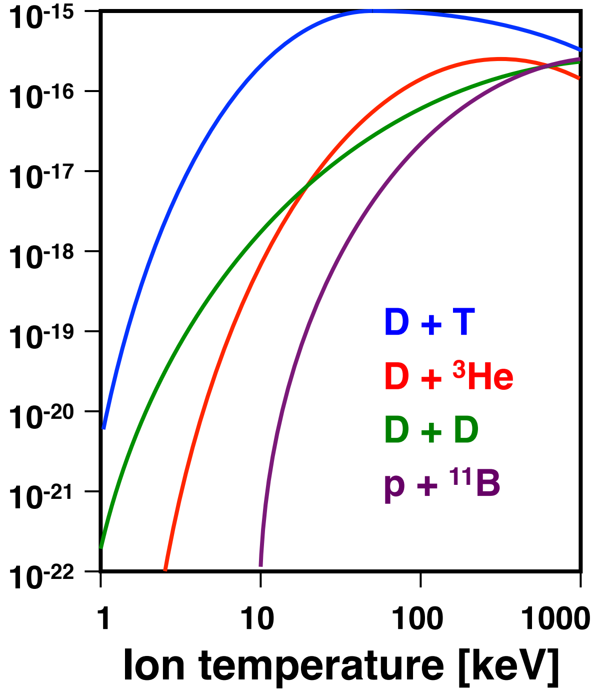


Larger at lower energies

Larger at higher energies

Greatest contribution to fusion rate

$\langle \sigma_{fus} v \rangle$ [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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You Can’t Live With Them

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

$$\frac{P_{ie}}{P_{fus}} \sim \frac{3\times10^{-16}\quad Z^3\quad \ln\Lambda}{E_{fus,\,MeV}\,\langle\sigma v\rangle_{cm3/sec}\, A\, T^{1/2}_{i,\,keV}} \left[\frac{T_i}{T_e}\right]^{3/2}$$

~ 1 for $Z\sim1$, $\ln\Lambda\sim20$, $E_{fus}\sim18$ MeV
$\langle\sigma v\rangle\sim2\times10^{-16}$ cm^3/sec,
$T_i/T_e\sim5$, $A\sim2$, $T_i\sim100$ keV

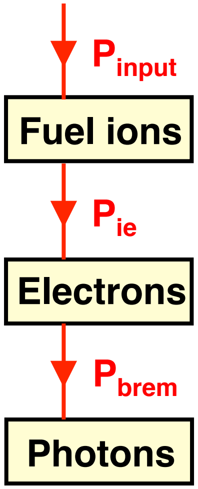
$P_{fus}>>P_{input}$, so $P_{ie}>>P_{input}$

Thus T_e must be ~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



P_{input}

Fuel ions

P_{ie}

Electrons

P_{brem}

Photons

Electrons Lose Energy via Bremsstrahlung Radiation

If photons are confined

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

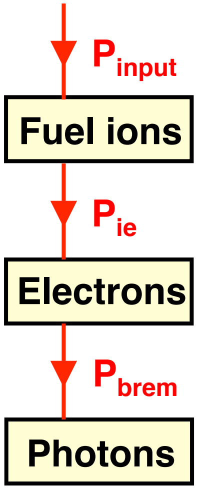
$$\frac{E_{photons}}{E_{ions}} \approx \frac{8\,\sigma_{SB}\,T^3}{3\,c\,k_B\,n_i}$$

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

Electrons Lose Energy via Bremsstrahlung Radiation

If photons are confined

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

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

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

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

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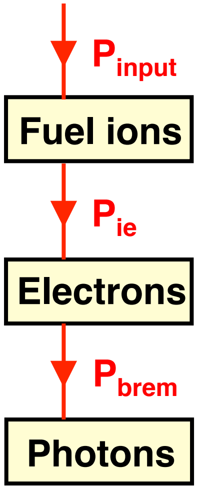

P_{input}

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P_{ie}

Electrons

P_{brem}

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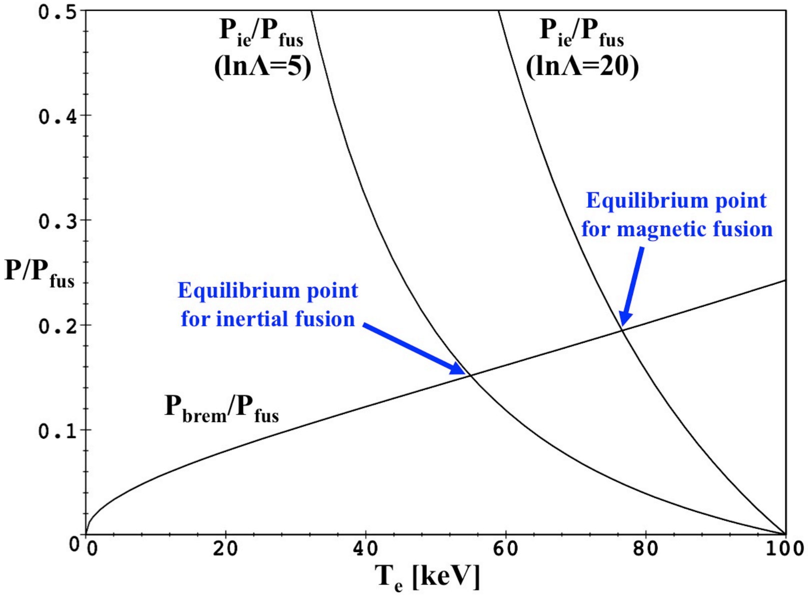
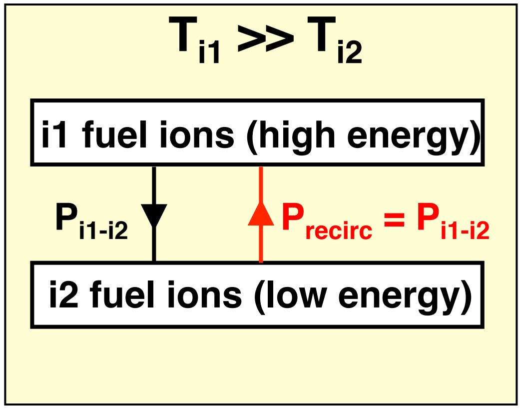
If photons escape

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)

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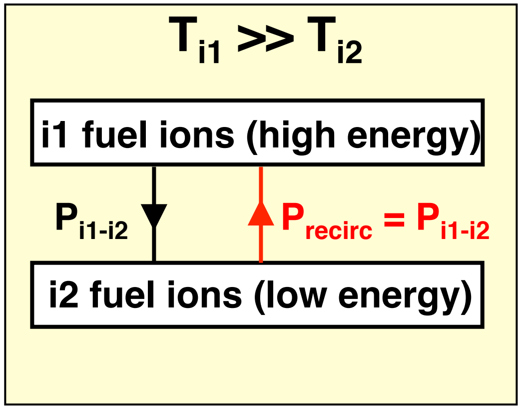

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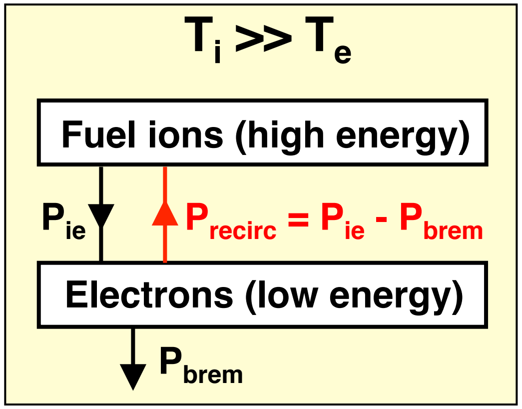

$T_i >> T_e$

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P_{ie}

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Electrons (low energy)

P_{brem}

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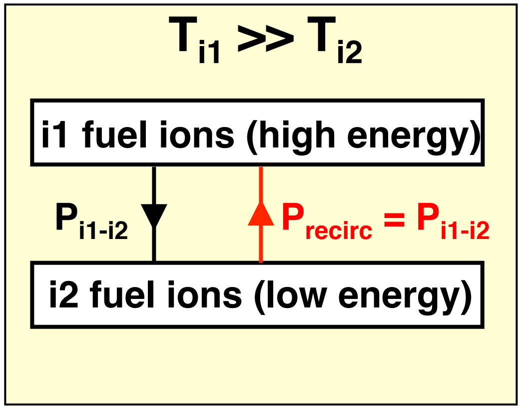

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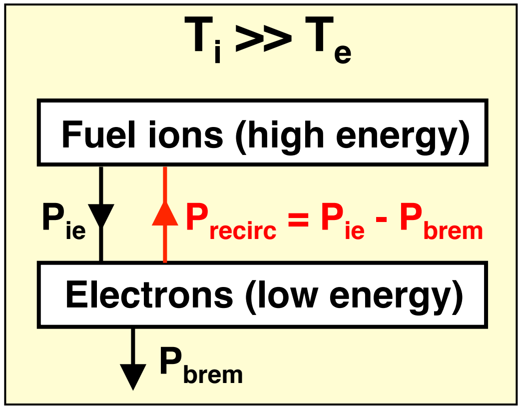

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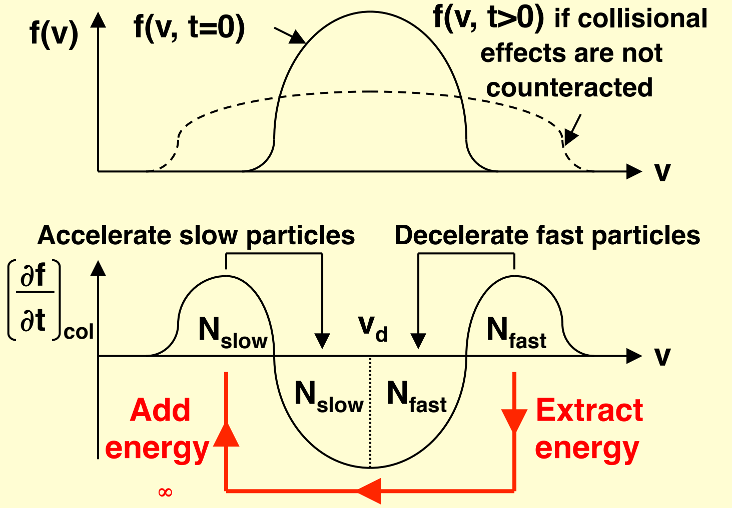
Non-Maxwellian Distribution f(v)



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

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

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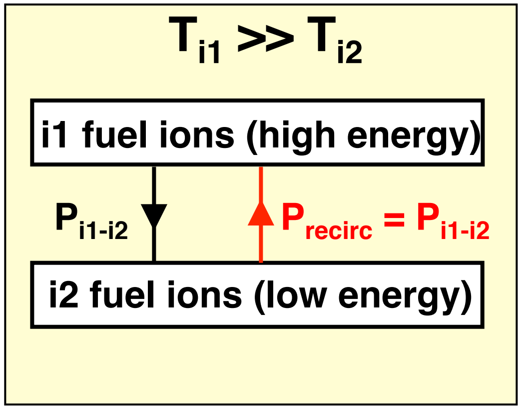

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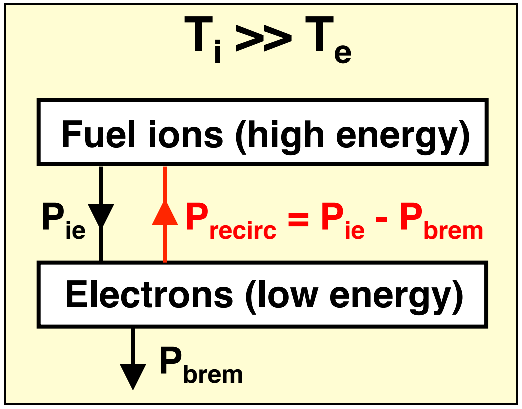

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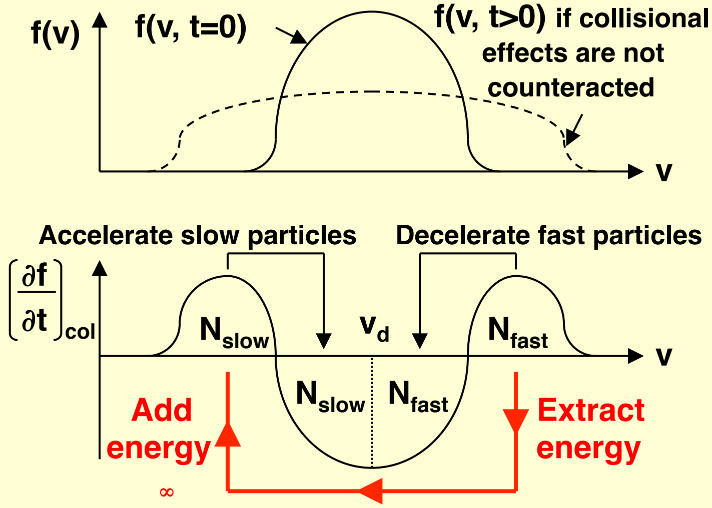

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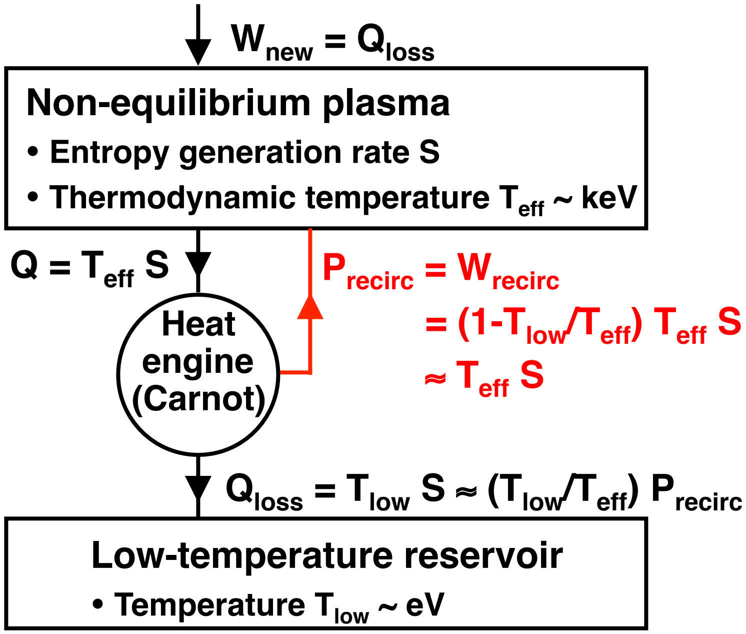
Idealized system for recirculating power to maintain a nonequilibrium plasma



↓ $W_{new} = Q_{loss}$

Non-equilibrium plasma
- Entropy generation rate S
- Thermodynamic temperature $T_{eff} \sim$ keV

$Q = T_{eff}\ S$ ↓

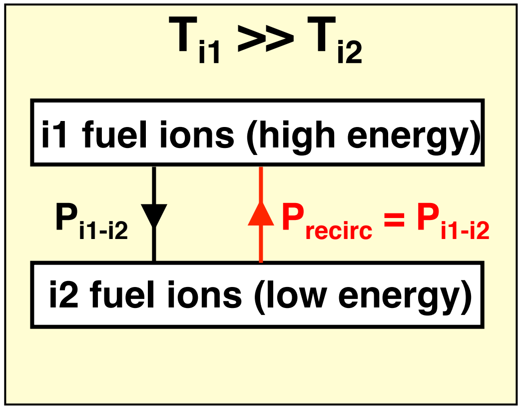
Heat engine (Carnot)

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

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

Low-temperature reservoir
- Temperature $T_{low} \sim$ eV

Required Power to Maintain a Nonequilibrium Plasma



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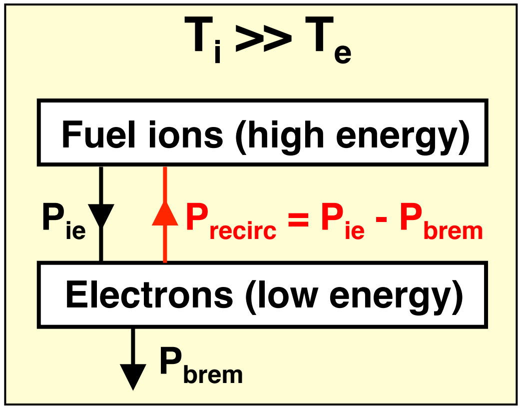

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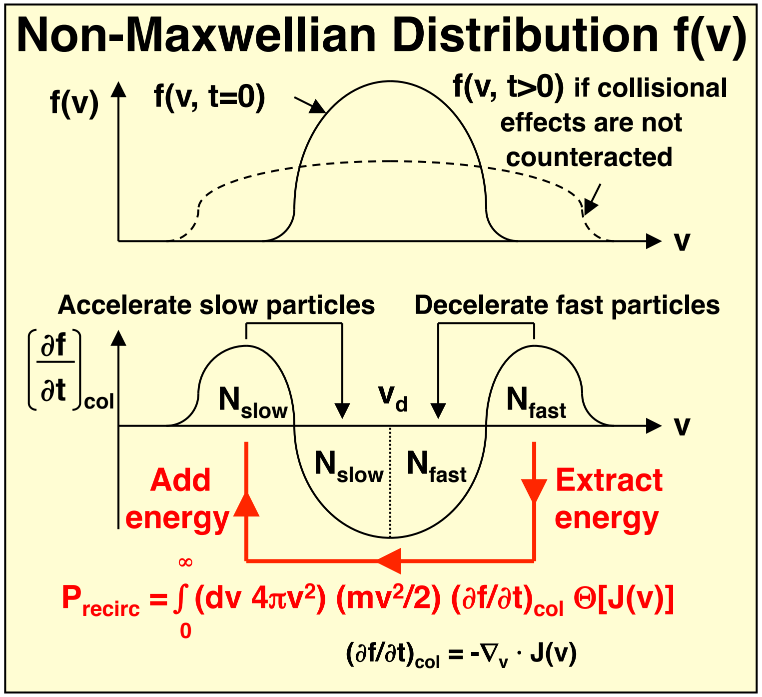

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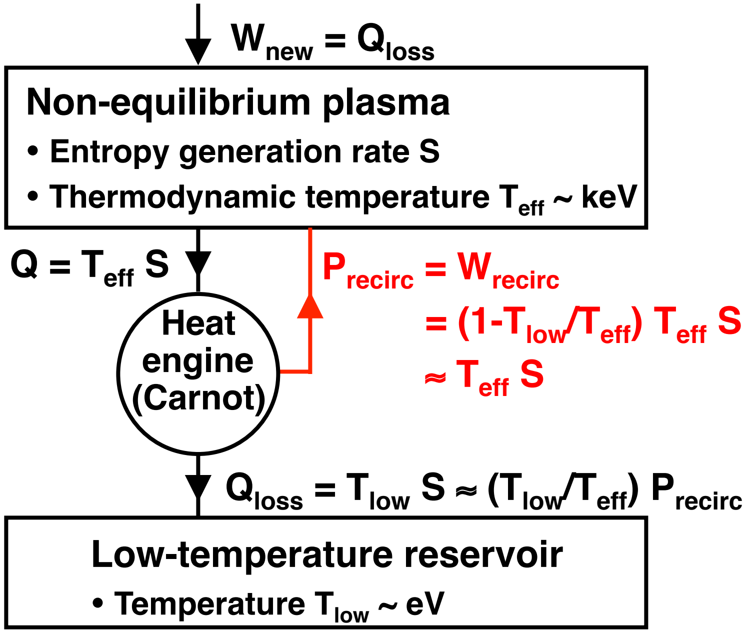

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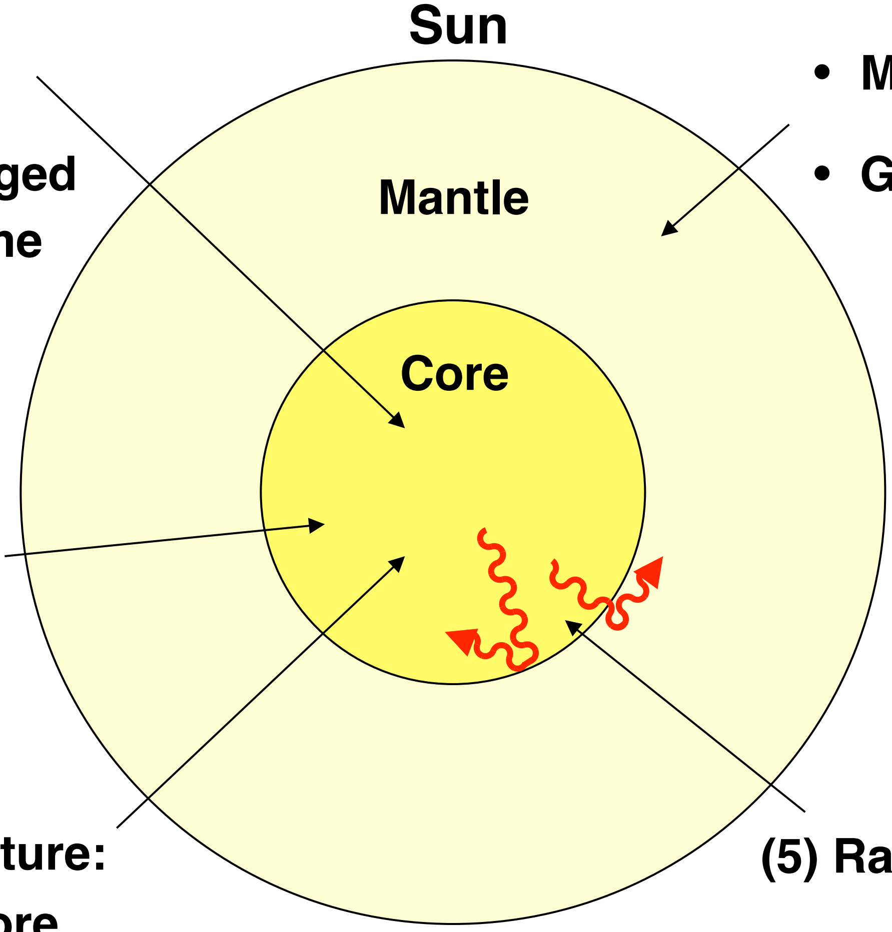
Low-temperature reservoir
- Temperature $T_{low} \sim$ eV

- $P_{recirc}/P_{fus} \sim$ 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 $P_{recirc} \gg P_{fus}$ 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:

- **$T_{rad} \approx T_i$**
- **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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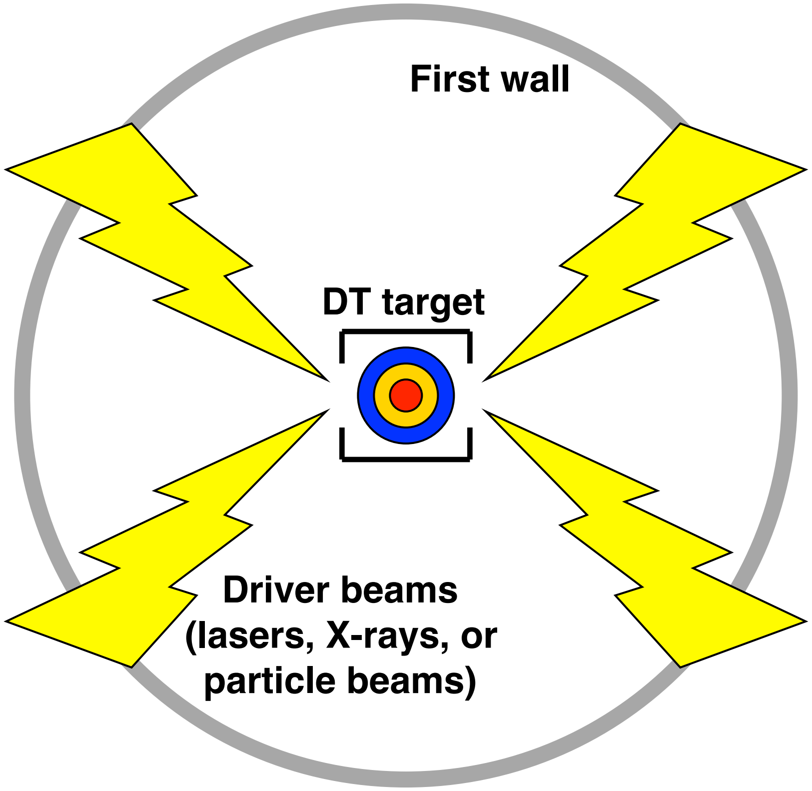
Inertial Confinement of Fusion Plasma

- 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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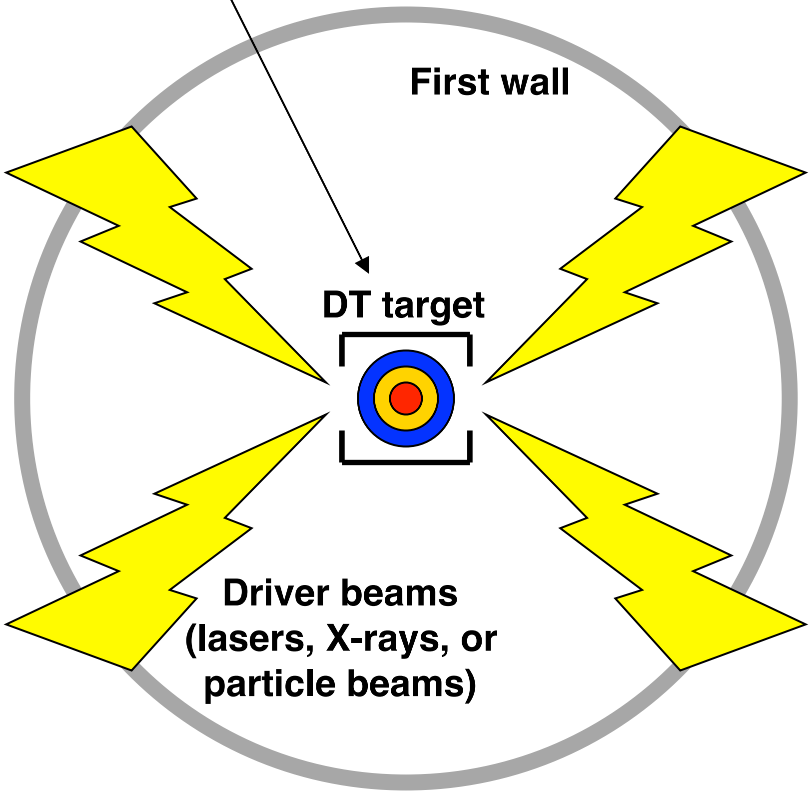
Major problems:

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



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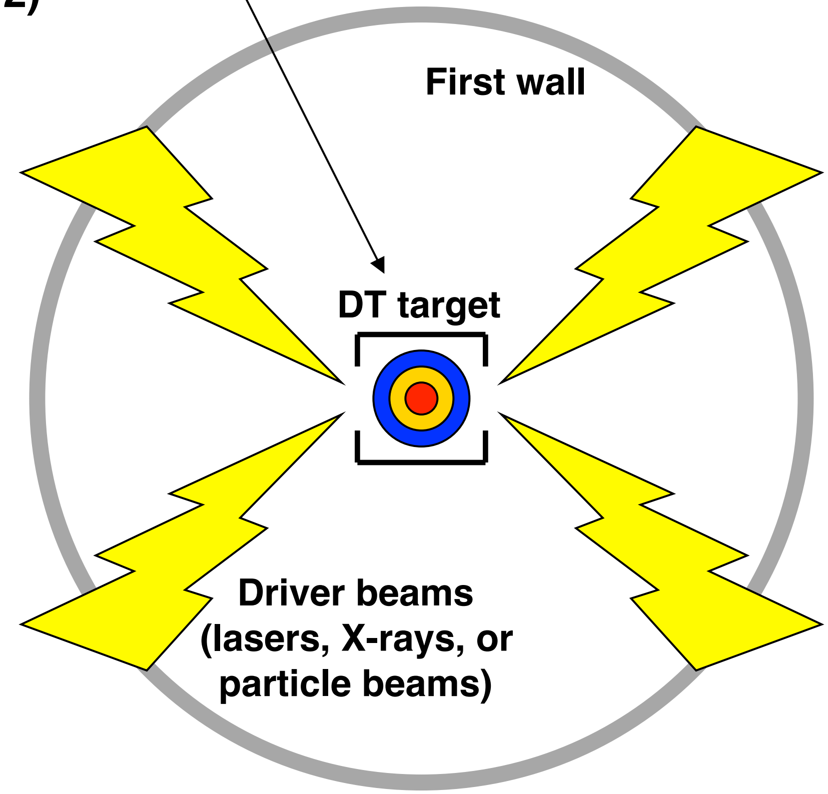

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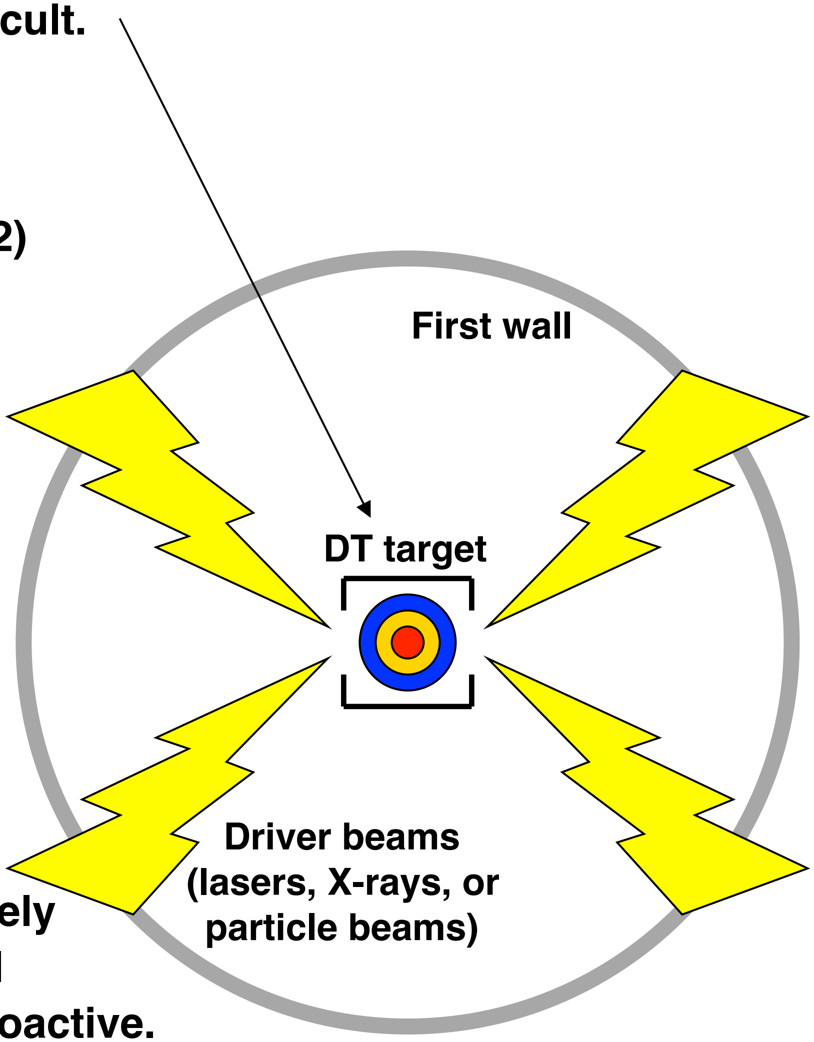

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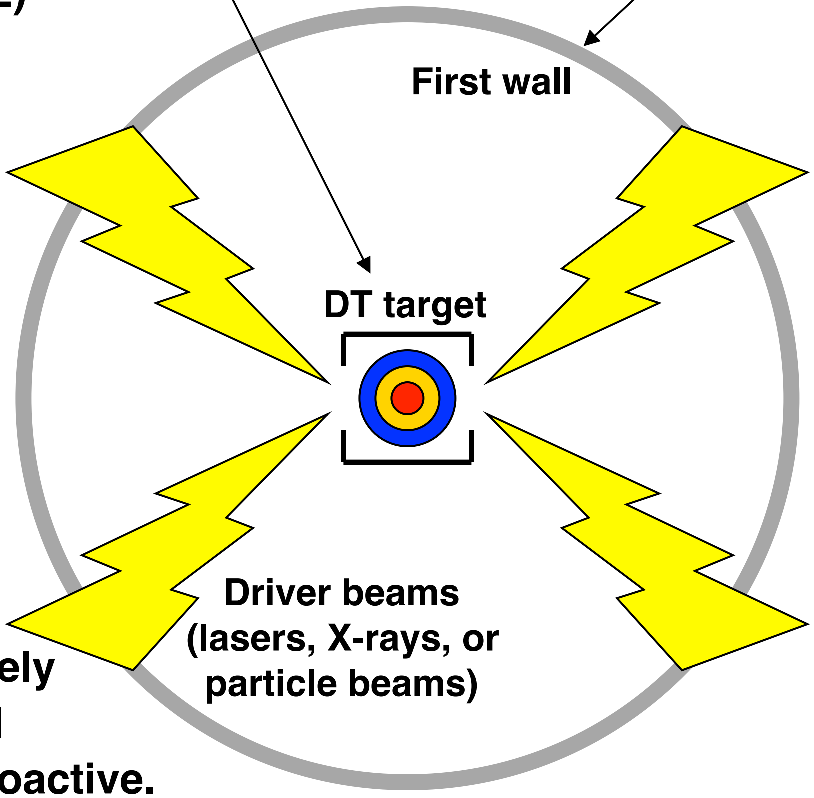

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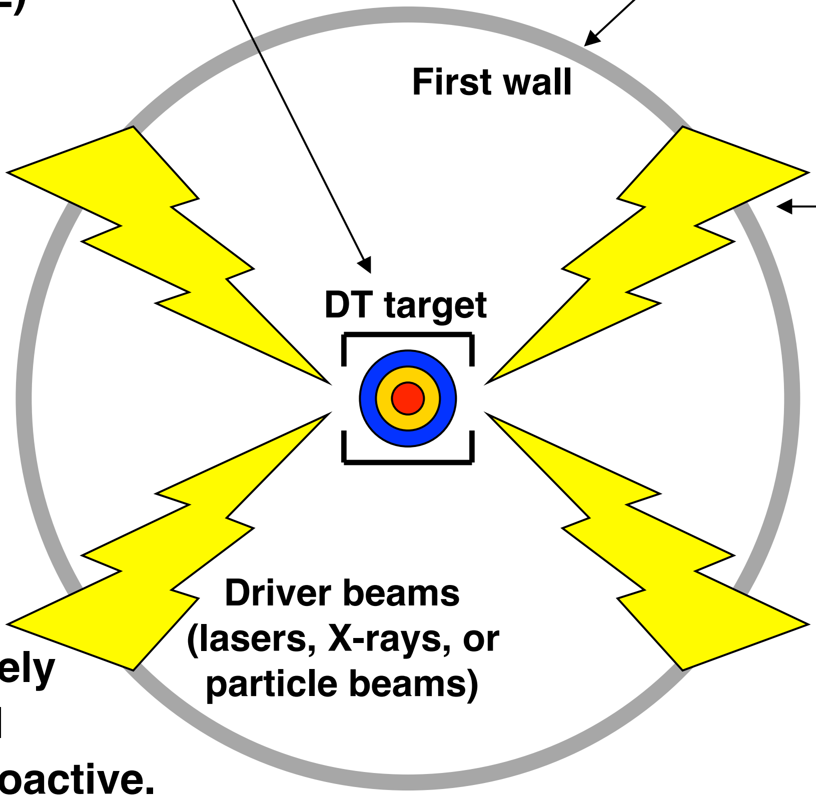

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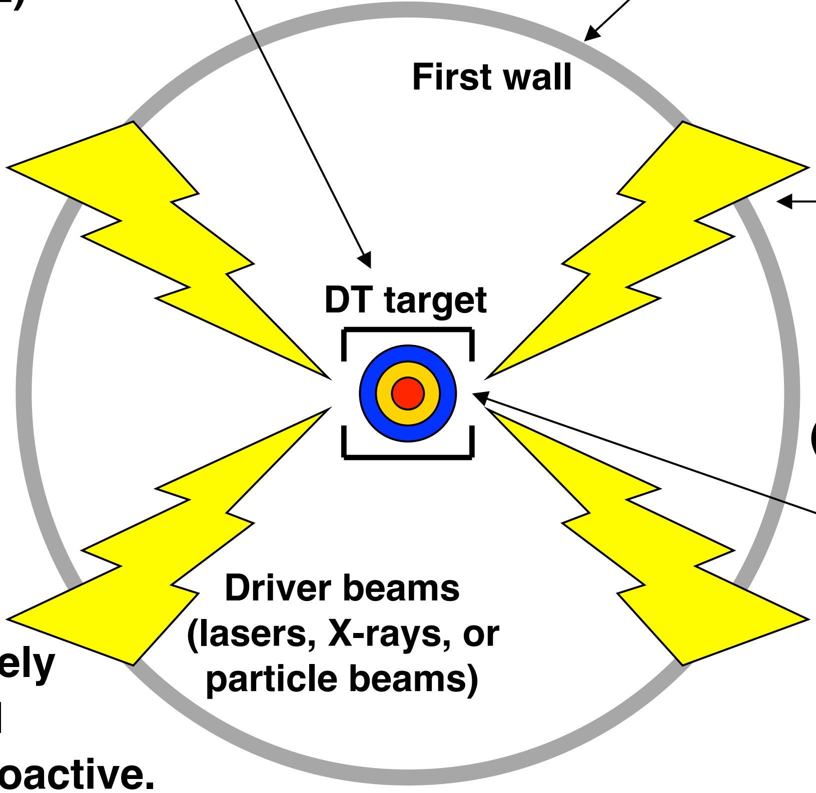

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(6) Lithium breeder material in walls must be converted into precisely fabricated DT targets and accurately positioned in chamber with throughput of several per second.

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 $\mathrm{GW}_{\text{thermal}}$ or 1 $\mathrm{GW}_{\text{electric}}$ 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 ~2.6x10^8 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?

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]

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?

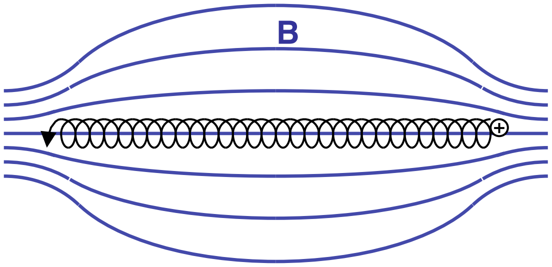
How many more decades would be required to achieve that goal?

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?

The most justifiable use of NIF may be as a "wind tunnel" for subscale modeling of nuclear weapons, astrophysical processes, etc., and as a WPA project to retain enough scientists/engineers with expertise relevant to nuclear weapons.

Magnetic Confinement of Fusion Plasma

Charged particles spiraling along magnetic field lines B cannot easily cross them to escape



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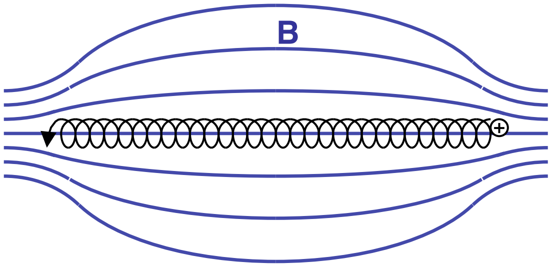

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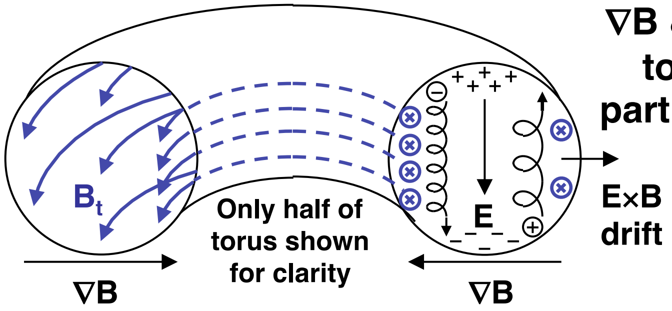
Solution 1: Eliminate the ends by bending lines into a closed toroidal field B_t



Problem 2: ∇B & E×B drifts together let particles escape

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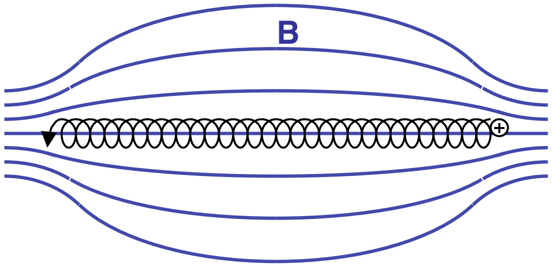

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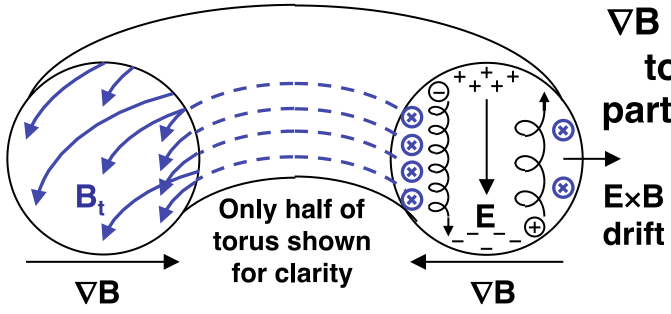
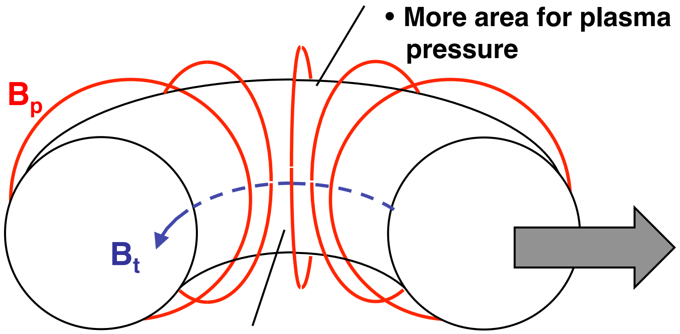


Problem 2: ∇B & $E \times B$ drifts together let particles escape

Solution 2: Add poloidal field B_p to mix particles in inner and outer regions of torus



Outer wall of torus:
- Less magnetic pressure
- More area for plasma pressure

Inner wall of torus:
- More magnetic pressure
- Less area for plasma pressure

Problem 3: Net outward force on plasma

Magnetic Confinement of Fusion Plasma

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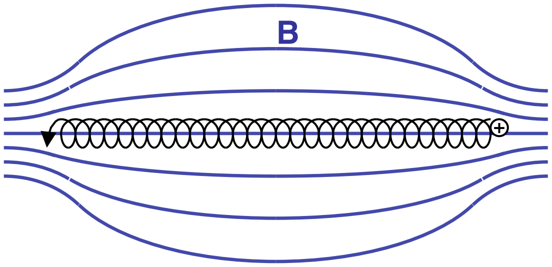

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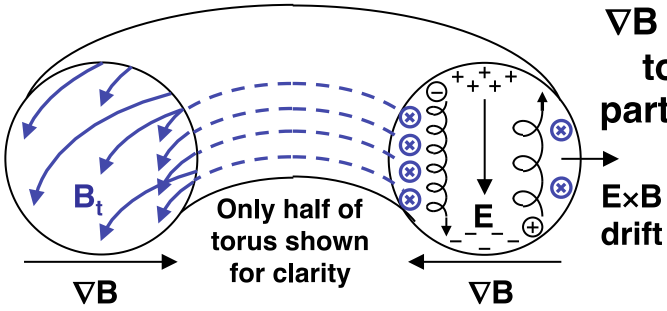

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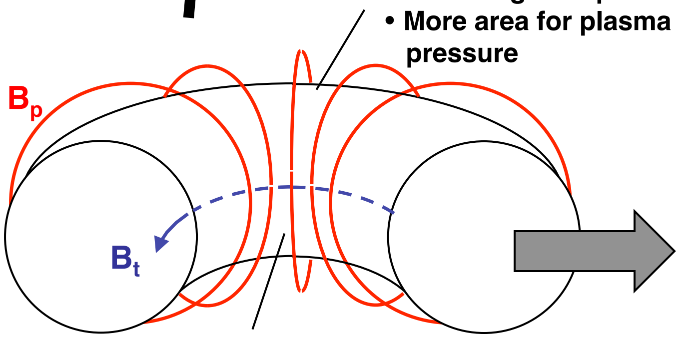

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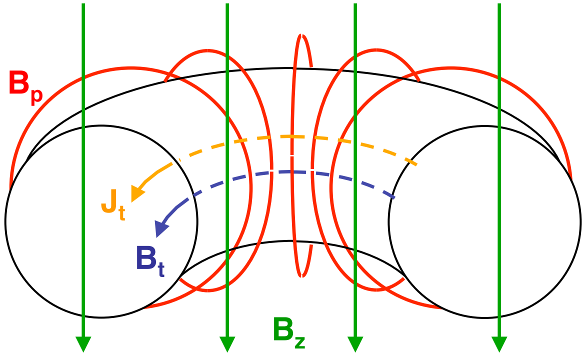
Problem 3: Net outward force on plasma

Solution 3: Add vertical field B_z that acts on toroidal current J_t to balance outward forces on plasma

Tokamaks, stellarators, RFPs, FRCs, etc. differ in how they create the plasma current and B_t, B_p, & B_z



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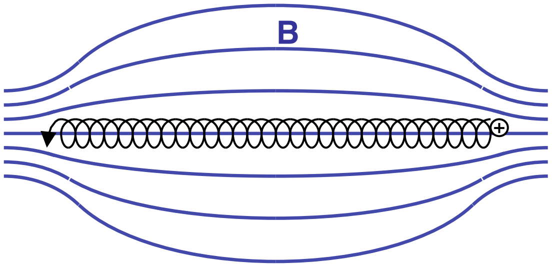

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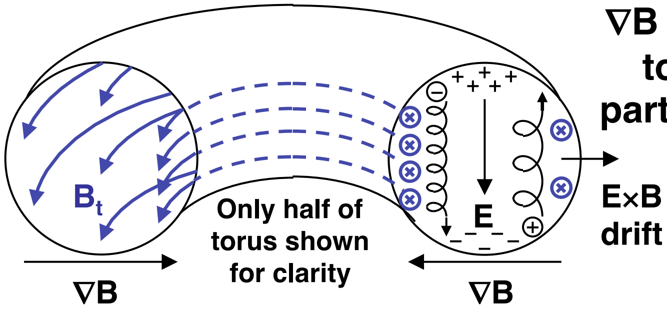

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<u>Goals (somewhat conflicting):</u>

Maximize $\beta \equiv$ plasma pressure / magnetic pressure

Minimize B inside plasma to avoid cyclotron radiation losses

Maximize fusion power density to minimize hardware cost

Inner hardware subject to radiation damage is inexpensive and easily accessible

Confine fuel ions and electrons but let charged products escape

Provide for lithium-6 blanket if necessary

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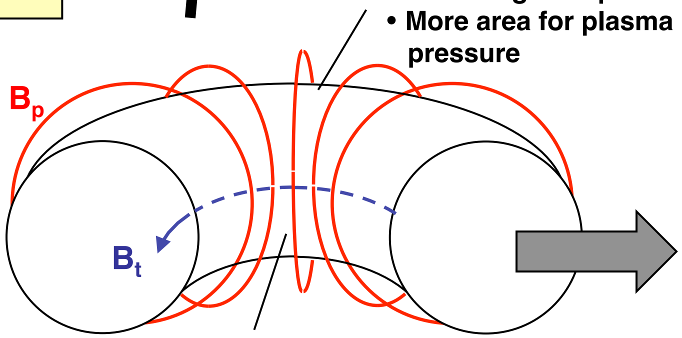

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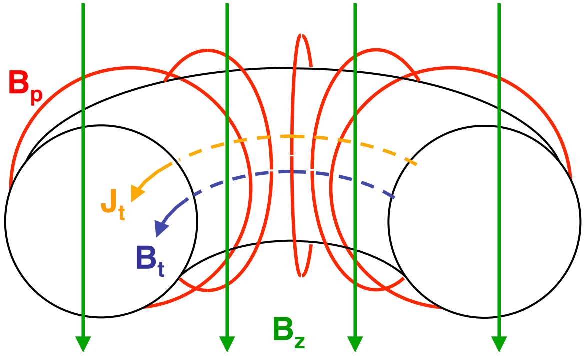
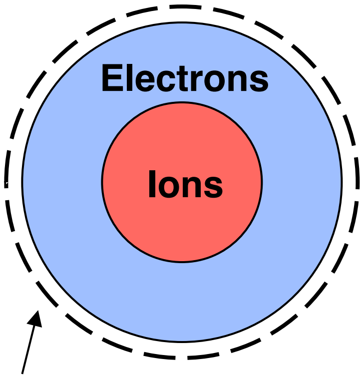


Other Confinement of Fusion Plasmas (1)

Electrostatic



High-voltage grid
or polyhedral cusp
magnetic field

- Electron potential well confines ions but ion upscattering losses are prohibitive
- Grid or cusp field confines electrons but electron losses are prohibitive

T.H. Rider 1995,
Phys. Plasmas 2:1853 & 1873

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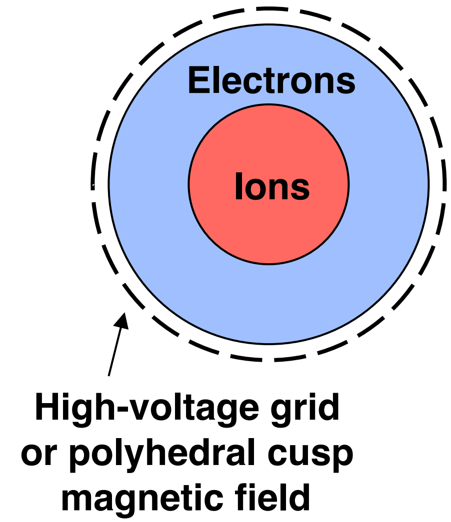

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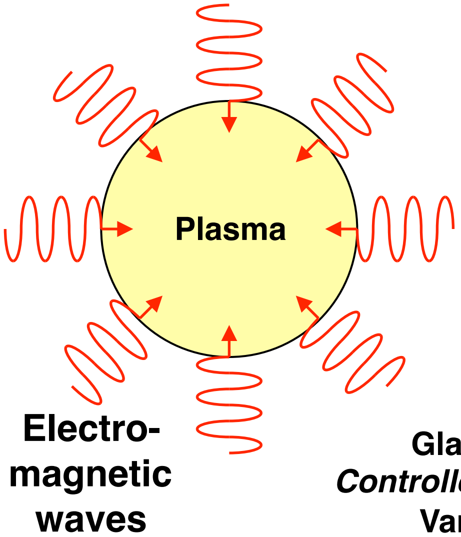

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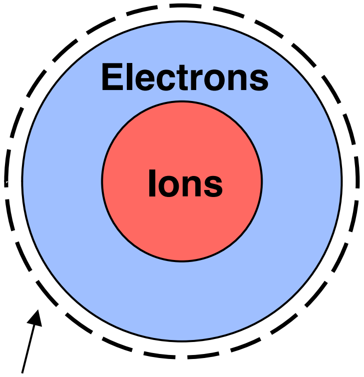

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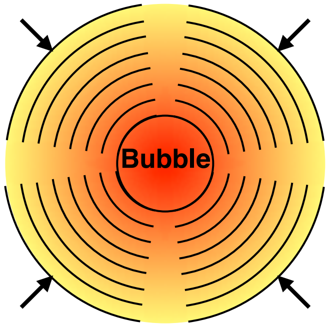
Acoustic: So No Fusion

Acoustic waves in deuterated acetone



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Taleyarkhan et al 2004, *Phys. Rev. E* 69:036109.
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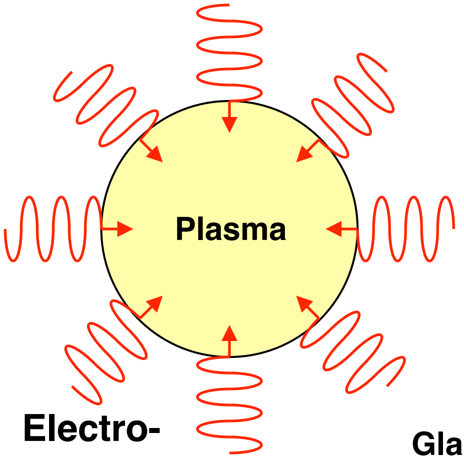

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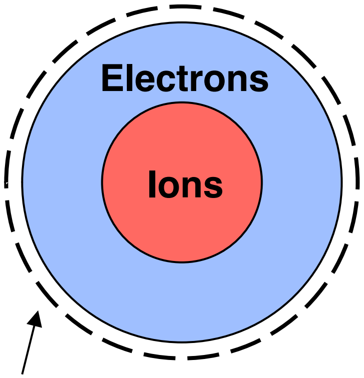

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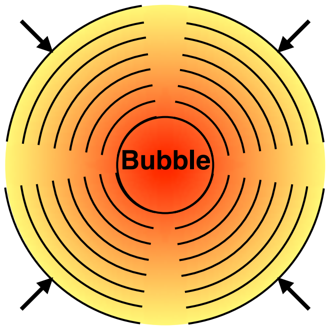

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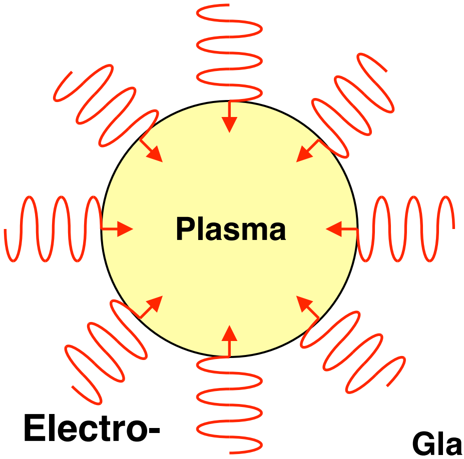

Electro-magnetic waves

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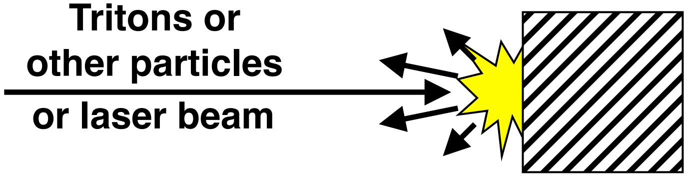
Beam + Solid Target



Tritons or other particles or laser beam

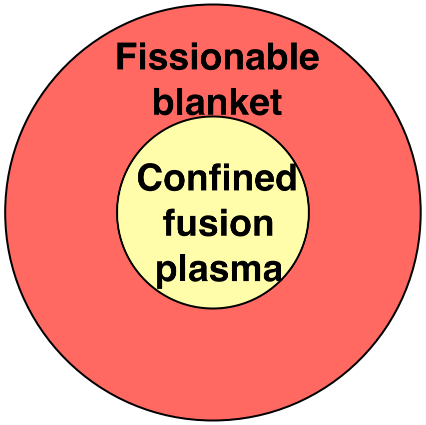
Solid deuterium target or other fuel

- Electrons in the target absorb and conduct away far too much of the beam energy for breakeven

Glasstone & Lovberg 1960, *Controlled Thermonuclear Reactions*, Van Nostrand, pp. 64-68

Other Confinement of Fusion Plasmas (2)

Fusion-Fission Hybrid



Has disadvantages of both fusion & fission:

- Fusion plasma requires expensive and complicated confinement system
- Fission blanket creates radioactive fission products and actinide waste
- Hybrid ICF pellets would blast fission products all over the target chamber

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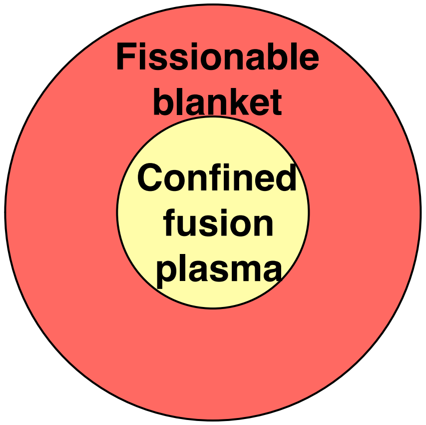

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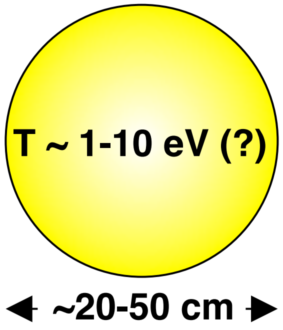
Ball Lightning

Observed lifetime > 2-5 sec



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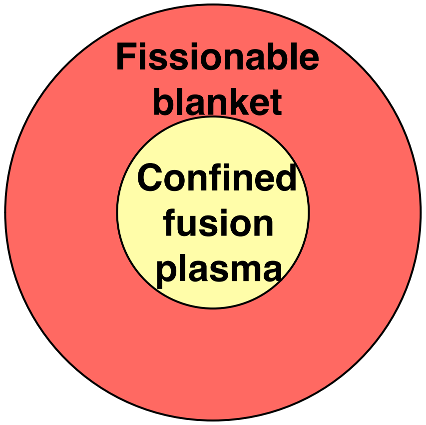

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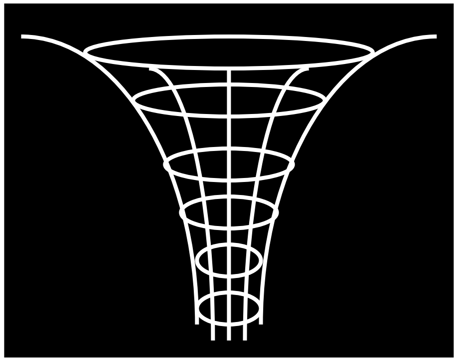
Small Black Hole

Compresses and heats matter to fusion conditions before it reaches the event horizon



- No signs of natural small black holes in our solar system
- Creating a black hole via implosion is orders of magnitude more challenging than even ICF

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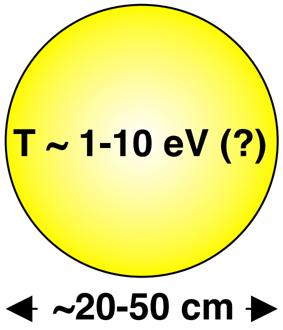

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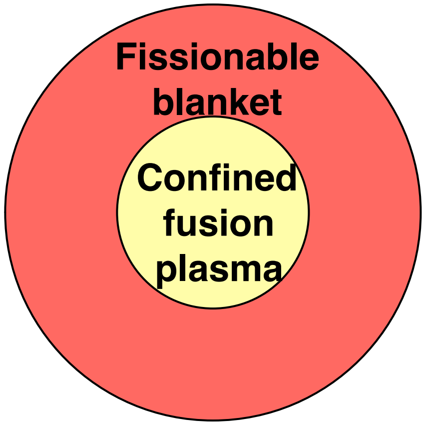

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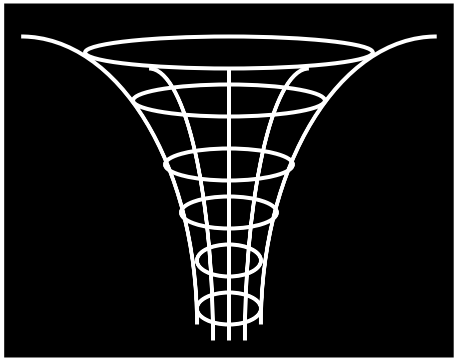

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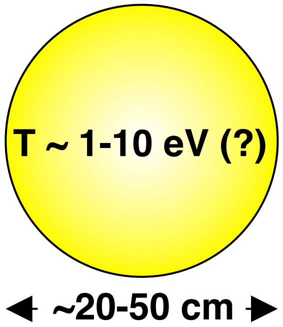

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- Are there other confinement approaches?
- Can one show that these ideas completely cover the phase space of confinement approaches?

Conversion to Electrical Energy

Heat

Carnot limit:

$$\text{Efficiency} < 1 - \frac{T_{min}}{T_{max}}$$

$$\sim 0.3 - 0.4$$

for $T_{min} \sim 300^{o}K$, $T_{max} \sim 500^{o}K$
(before something melts)

- Conventional methods add moving parts and fluids
- Thermoelectric conversion
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Light nuclei (p^+, α, etc.)

Direct converter problems in magnetic plasmas[1]:

- **Field that lets enough fusion products out lets too many fuel ions & electrons escape**
- **Arcing at high voltages and densities**

Inverse ion accelerators?[2]

Other methods?

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Heavy (e.g., recoil) nuclei

Travel <10 um in solids—

- Difficult for them to reach a direct electric converter before their K.E. becomes heat
- Widely spaced <10-um-thick sheets are theoretically feasible but generally impractical

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Ronen 2004, *Nucl. Instr.* A522:558

Slutz 2003, *Phys. Plasmas* 10:2983

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Neutrons

Novel methods of extracting energy from:

- Neutrons directly???
- Recoil nuclei hit by neutrons
- (n,γ)-produced gamma rays
- Electrons excited by those gamma rays

L.J. Perkins et al 1986, UCRL-93988

and 1988, *Nucl. Instr. Methods* A271:188

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L.J. Perkins et al 1986, UCRL-93988

and 1988, *Nucl. Instr. Methods* A271:188

Photons (esp. X & γ rays)

Let photons impart their energy to electrons via:

- Photoelectric effect
- Compton scattering
- Pair production
- Etc.

Then extract that energy from the electrons

L.L. Wood et al 1973, UCID-16229 & 16309

Fundamental Constraints on Fusion Approaches

(Barring Miracles—Wait One Slide…)

Fusion approaches that do not appear suitable for practical power-producing reactors:

- Nonmagnetic confinement (inertial, electrostatic, electromagnetic, and acoustic), excluding stars and bombs
- Plasma systems operating substantially out of thermodynamic equilibrium
- Advanced aneutronic fuels (^{3}He+^{3}He, p+^{11}B, p+^{6}Li, etc.)
- Most high-efficiency direct electric converters

T. H. Rider 1995, Ph.D. thesis, MIT

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Best foreseeable 1 GW$_e$ (3 GW$_t$) magnetic fusion reactors:

- D+T: 2.4 GW of 14-MeV neutrons, 1.6 giga-Curies (GCi) of T stockpile/year
- D+D w/o product burnup: 1 GW 2.5-MeV neutrons, 1 GW X-rays, 70 GCi T
- D+D with product burnup: 1.1 GW mainly 14-MeV neutrons, 180 MW X-rays
- D+^{3}He w/o product burnup: 30 MW 2.5-MeV neutrons, 500 MW X-rays, 1.8 GCi T
- D+^{3}He with product burnup: 150 MW mainly 14-MeV neutrons, 500 MW X-rays
- Mainly thermal (Carnot-limited) conversion of fusion energy to electricity

---

T. H. Rider 1995, Ph.D. thesis, MIT

Potential Thesis (or Nobel Prize) Topics

Fusion reactions:

- **In the table of possible fusion reactions, should additional reactions be green?**
  (Consider competing side reactions and idealized breakeven against bremsstrahlung.)
- **Are there any promising reactions not in the table (due to higher Z or shorter nuclide half-life)?**

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Can one provide better evidence (especially experimental) for or against spin polarized fusion?

- **Benefits of spin-polarized fusion (especially for D+D reaction enhancement or suppression).**
- **Methods of producing polarized nuclei.**
- **Mechanisms and rates of depolarization relative to the fusion rate.**

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- **Are there more efficient muon production methods?**
- **Are there practical methods for unsticking muons from alpha particles?**
- **Are there methods to reduce the muon catalysis cycle time?**
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- **Can the effective electron mass or charge be increased in useful ways?**

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Other ways to improve the tunneling factor:

- Is there a way to keep scattering from hindering shape-polarized fusion?
- Is the resonant tunneling model valid, and does it have useful consequences?
- Is fusion of light elements in liquid metallic states scientifically valid and practical to achieve?
- Are there other ways to improve the tunneling factor?
- Can one prove we have covered the complete phase space of ideas for improving the tunneling factor?

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Other improvements to σ_{fus}:

- Are there ways to improve the wavefunction cross-sectional area factor in σ_{fus}?
- Are there ways to improve the Breit-Wigner compound nucleus energy resonance factor in σ_{fus}?
- Are there any other categories of ways to influence σ_{fus}?

More Potential Thesis (or Nobel Prize) Topics

Fusion products:

- **Are there practical ways to influence the reaction channels and products?**

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- **Are there practical ways to reduce ion-electron energy transfer or recirculate power from the electrons back to the ions?**
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Confinement of particles and energy:

- Are there practical lessons we can learn from stellar fusion and use to improve fusion reactors?
- Are there ways to overcome the main practical difficulties with inertial confinement fusion?
- Which existing magnetic confinement approach is best, or can a better one be created?
- Can the conduction losses be reduced to make acoustic confinement practical?
- Can fusion-fission hybrids be made more attractive?
- How is ball lightning confined, and can fusion reactors employ a similar approach?
- Is there any feasible way to create a small black hole?
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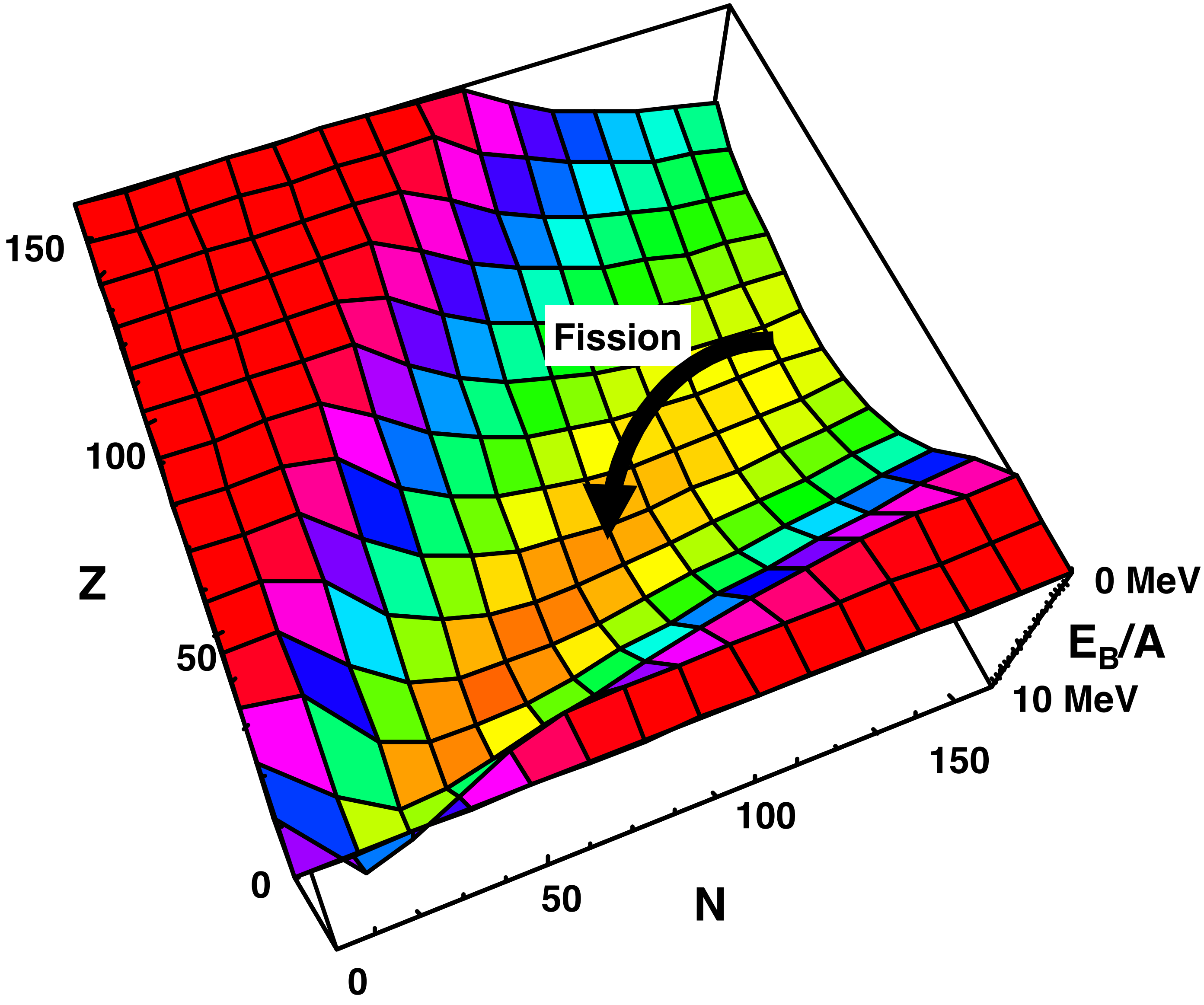
Conversion to electrical energy:

- **What are the most efficient and/or most compact thermal-to-electric converters?**
- **What are the best converters for light nuclei—inverse linear accelerators, inverse cyclotrons, etc.?**
- **Are there practical ways to directly convert the energies of recoil nuclei or other heavy nuclei emitted by solid materials?**
- **What are the best converters for electrons?**
- **How practical and efficient can neutron energy conversion methods be [Perkins 1986, 1988]?**
- **How practical and efficient can X-ray and γ-ray energy conversion methods be [Weaver 1973]?**

Binding Energy per Nucleon And Methods of Tapping It



Fission Process

$$\frac{E_{Coulomb}}{E_{surface}} \propto \frac{Z^2}{A} \sim \text{0.4 Z for heavy nuclei}$$

Fission barrier height:

$V_B \sim 9\ A^{2/3}\ [1 - (Z^2/A)/49]$ MeV

$$+ \begin{cases} \text{0.3 MeV} & \text{if odd-odd} \\ \text{0 MeV} & \text{if odd-even} \\ \text{-0.3 MeV} & \text{if even-even} \end{cases}$$

\+ shell corrections

~ 5.6 MeV for even U/Pu isotopes

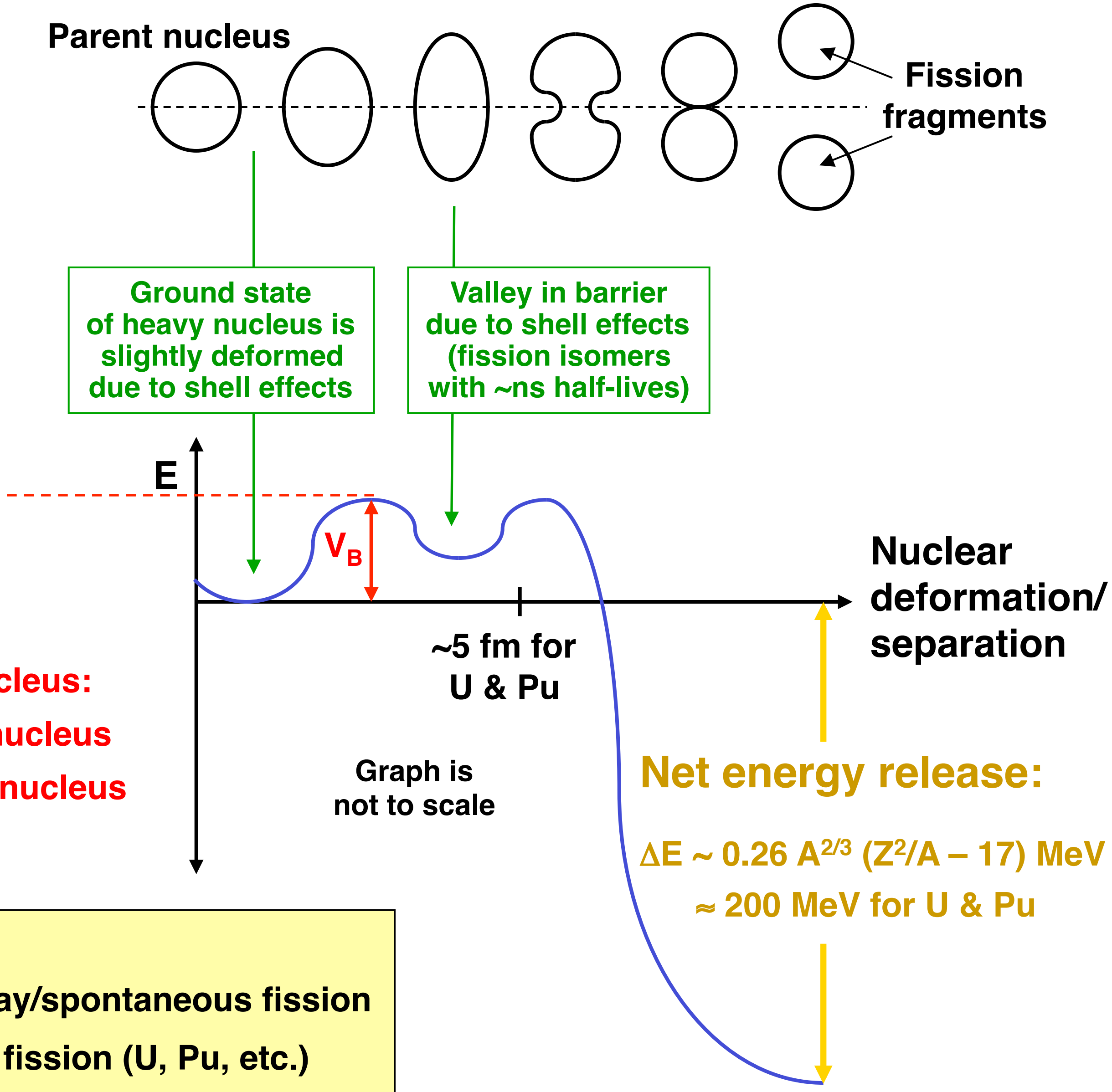
~ 6.2 MeV for odd U/Pu isotopes

Captured neutron adds energy to nucleus:

~ 5 MeV for even U/Pu compound nucleus

~ 6.5 MeV for even-odd compound nucleus

- $Z<90$: barrier too high for fission
- $Z>96$: barrier too low; rapid α decay/spontaneous fission
- Even-Z nuclei generally better for fission (U, Pu, etc.)
- Odd-N target nuclei generally better for n-induced fission (^{235}U vs. ^{238}U, etc.)



Ground state of heavy nucleus is slightly deformed due to shell effects

Valley in barrier due to shell effects (fission isomers with ~ns half-lives)

Net energy release:

$\Delta E \sim 0.26\ A^{2/3}\ (Z^2/A - 17)$ MeV

$\approx$ 200 MeV for U & Pu

Fission Fuels and Sources

Energy Production

Only 3 natural actinide resources:

^{235}U

- Directly useful as fuel
- Naturally mixed with ^{238}U
- $>3\times10^{8}$ kg readily accessible to mining
  → $>3\times10^{5}$ GWe-years (1/3 thermal effic.)
  → >15 years of present global energy consumption rate

^{238}U

- Transmute to ^{239}Pu fuel in breeder reactor
  $(n + {}^{238}\text{U} \rightarrow {}^{239}\text{U} \xrightarrow{\beta} {}^{239}\text{Np} \xrightarrow{\beta} {}^{239}\text{Pu})$
- $>4\times10^{10}$ kg readily accessible to mining
  → $>4\times10^{7}$ GWe-years
  → >2000 years of global consumption

^{232}Th

- Transmute to ^{233}U fuel in breeder reactor
  $(n + {}^{232}\text{Th} \rightarrow {}^{233}\text{Th} \xrightarrow{\beta} {}^{233}\text{Pa} \xrightarrow{\beta} {}^{233}\text{U})$
- $>8\times10^{9}$ kg readily accessible to mining
  → $>8\times10^{6}$ GWe-years
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Anderson 1989, *A Physicist's Desk Reference*, AIP. www.iea.org. yearbook.enerdata.net. www.world-nuclear.org.
Anno et al 2003, Actinides Critical Masses and the Paxton Woodcock Rule, *Proc. ICNC* 2003:71.

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Energy Storage

Most fissile isotopes that can be artificially produced:

^{242m}Am

- Critical mass ≈ 23 g dispersed in water
- 141-year half-life
- Small quantities produced in U or Pu reactors; final step is $^{241}\text{Am}(n,\gamma)^{242m}\text{Am}$

^{245}Cm

- Critical mass ≈ 47 g dispersed in water
- 8500-year half-life
- Small quantities produced in U or Pu reactors

^{254}Cf

- Spontaneous fission dominates decay
- 60.5-day half-life
- Minute quantities produced in reactors

Anderson 1989, *A Physicist's Desk Reference*, AIP. www.iea.org. yearbook.enerdata.net. www.world-nuclear.org.
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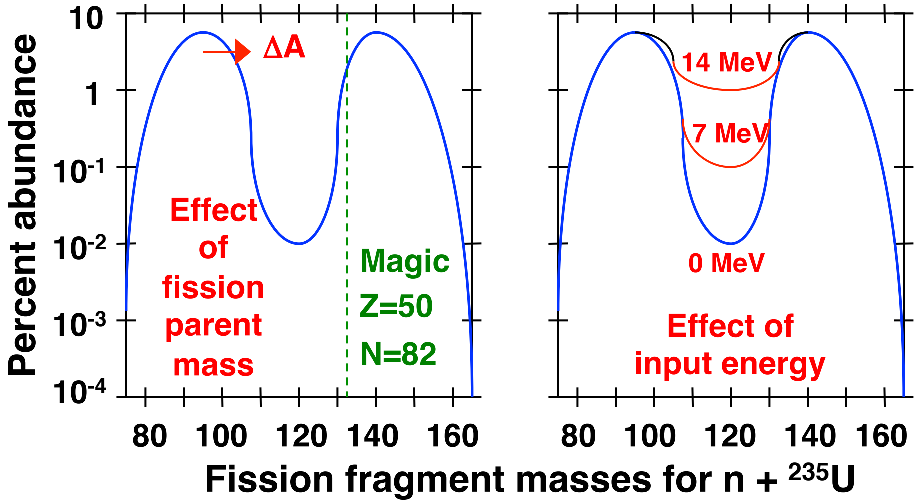
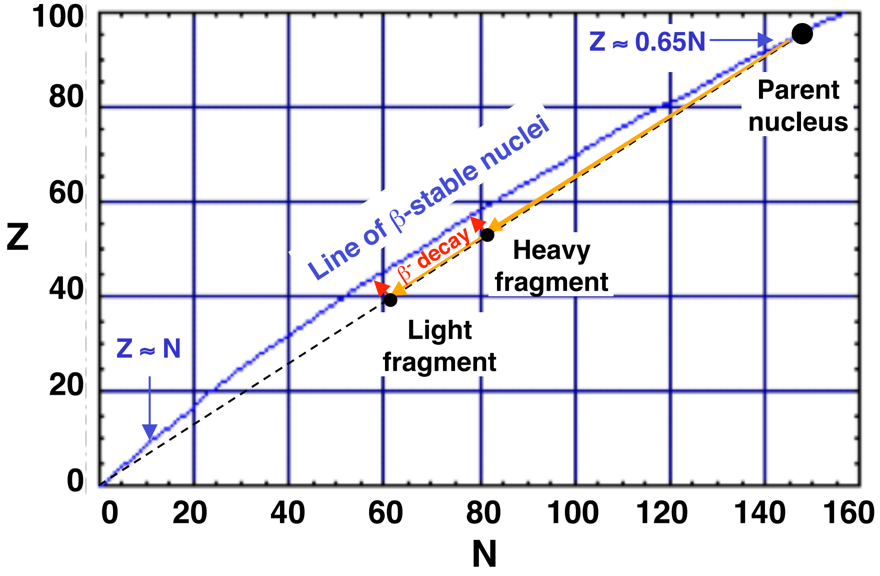
Fission Waste Production

Fission fragments

Asymmetric & wide range of fragments



Fragments must be β^- emitters



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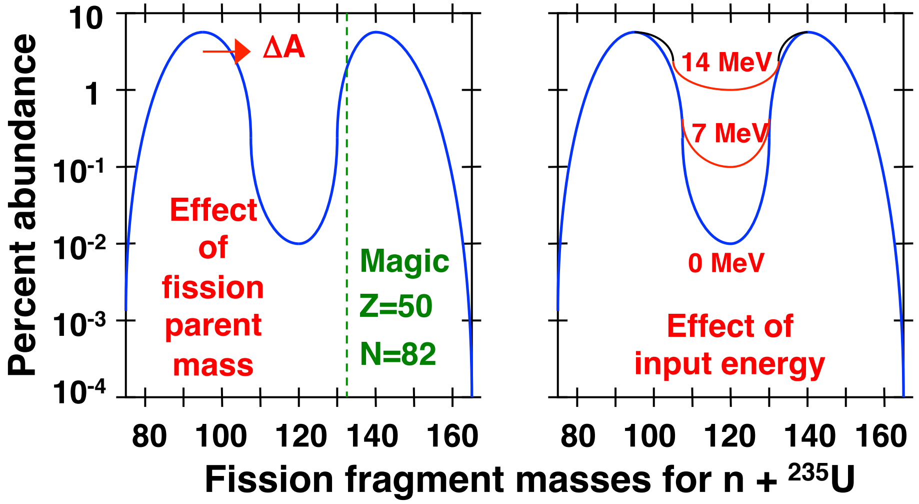

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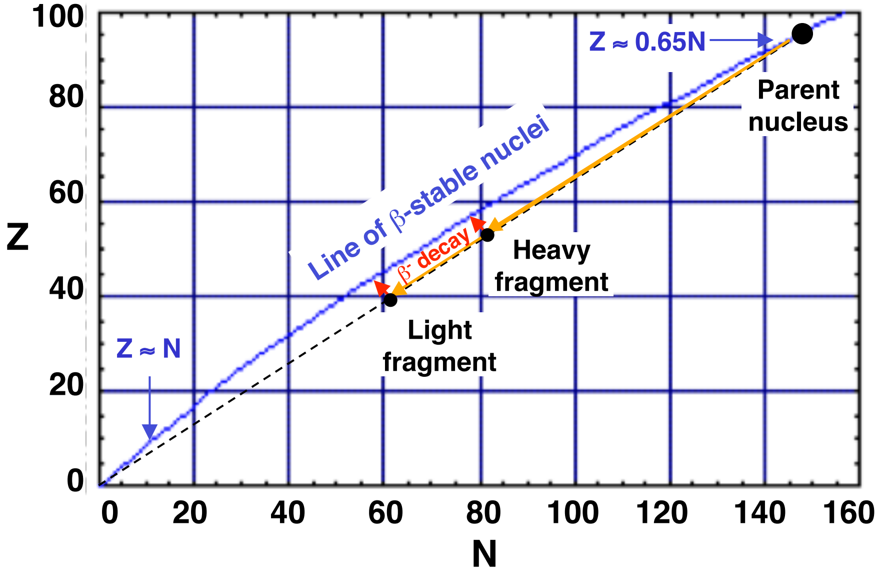
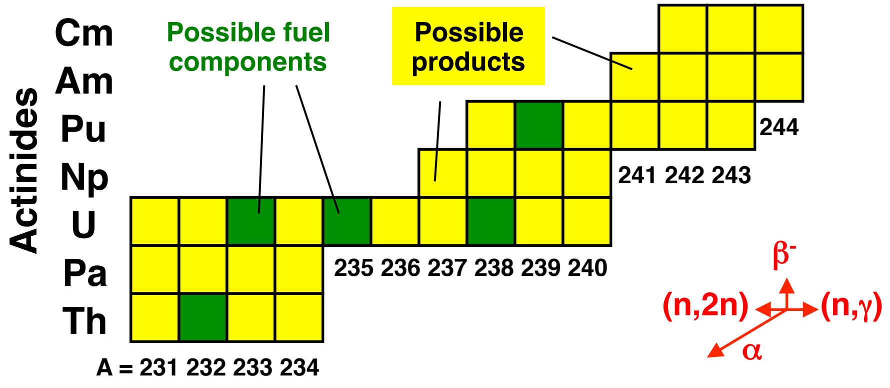


Neutron activation within fuel



- Few choices for fissile fuel to control products
- Eliminating other actinides from fresh fuel reduces waste but makes fuel a proliferation & criticality hazard and also prevents breeding

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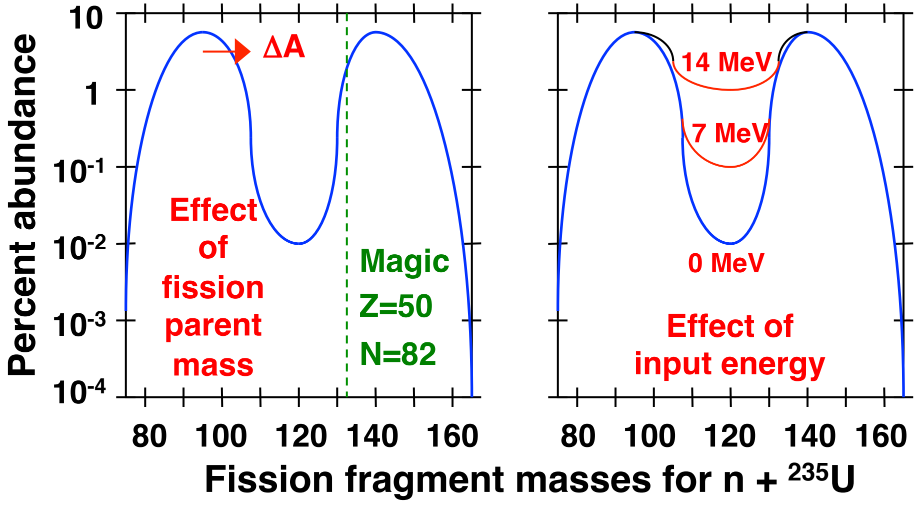

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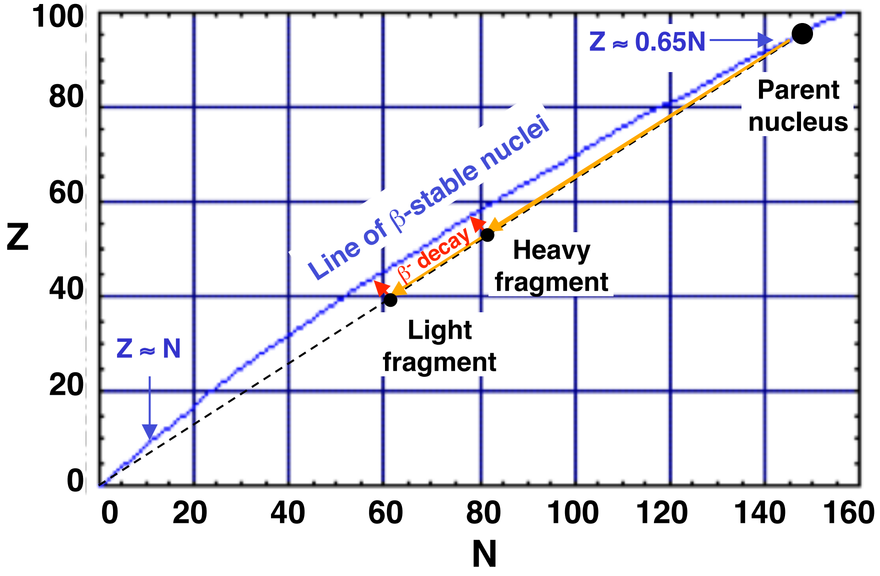

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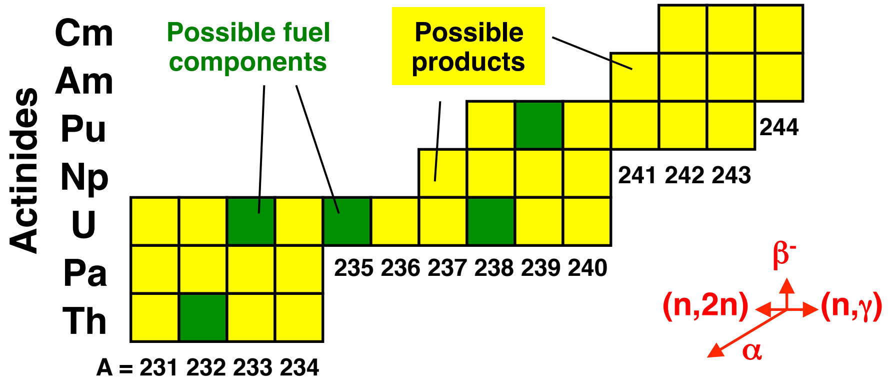

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Other neutron activation

Low-activation materials

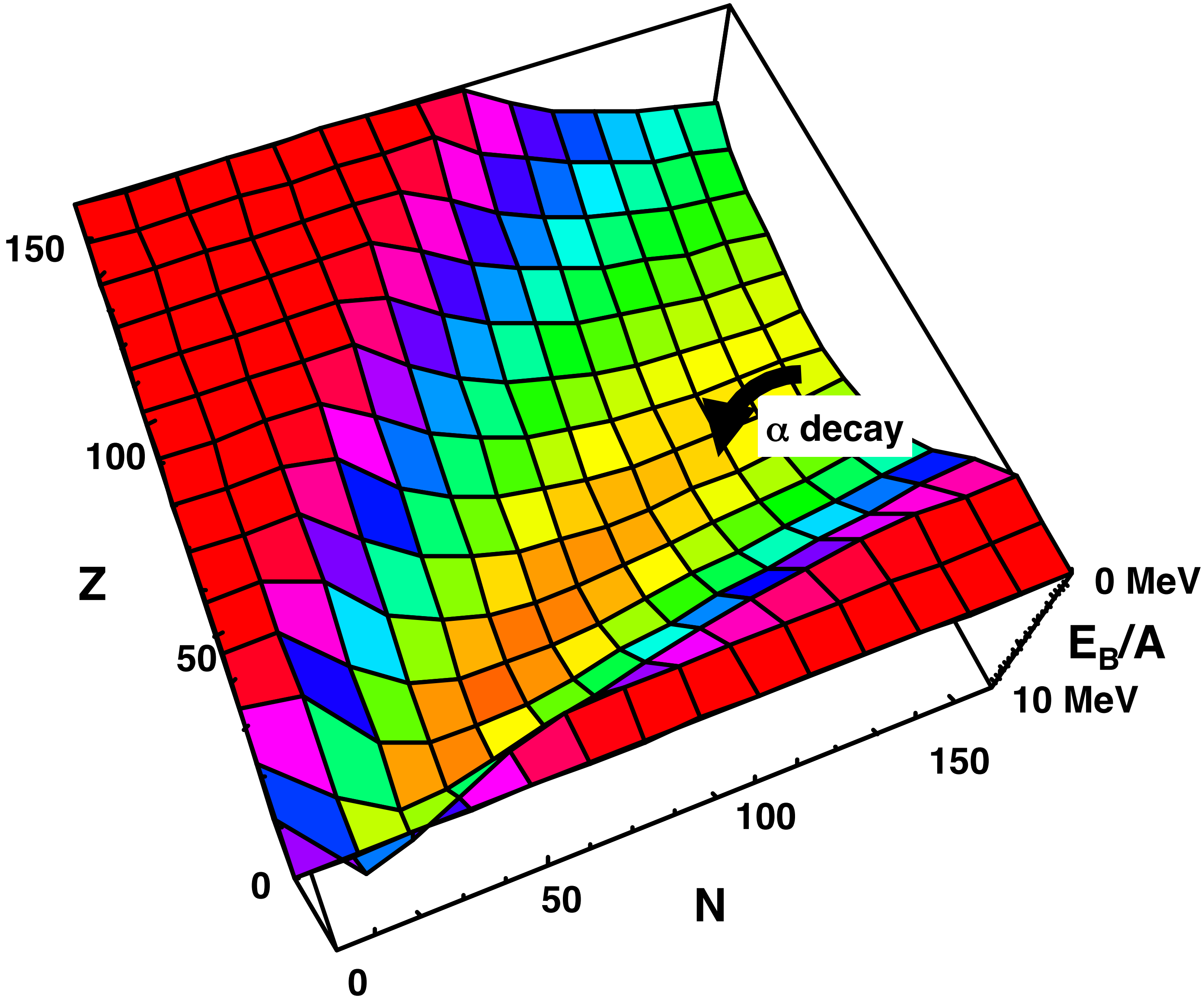
Moderators:	H_2O, D_2O, ^{12}C, etc.
Coolants:	H_2O, D_2O, ^{23}Na, etc.
Control rods:	^{10}B, ^{113}Cd, etc.
Reflectors:	^{9}Be, ^{12}C, etc.
Structural metals:	^{94}Zr, ^{98}Mo, etc.

- Some tritium is produced by D_2O, ^{10}B, etc.
- Still room for improvement in low-cost, high-temperature alloys that minimize activation or embrittlement by neutrons

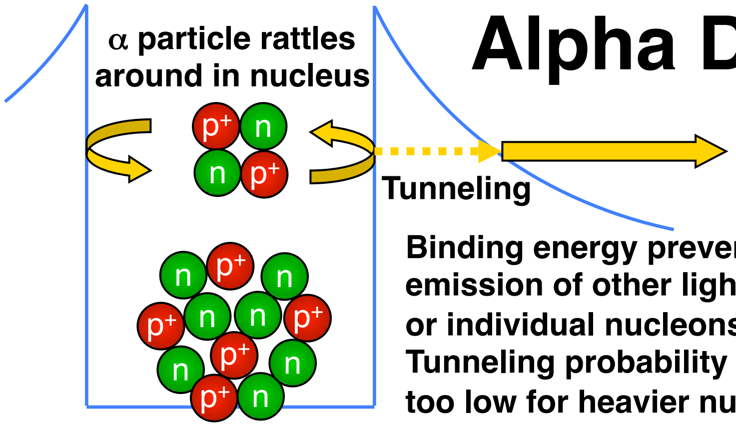
Fission Power

- **Are there any ways to intervene at the nuclear level to make the fission process cleaner, easier, or better?**
- **What are the best sources and methods for obtaining fission fuel?**
- **What are the best materials to use in fission reactors?**
- **What are the safest, cheapest reactor designs for using fission fuel?**
- **What are the most efficient methods for converting fission energy to electrical energy? (Convert fission fragment K.E. to electric energy?)**
- **What are the most efficient methods for harnessing fission energy for rocket propulsion?**
- **What are the best ways of separating/reusing/burning up/storing waste?**
- **What are the best ways to make fission reactors resistant to accidents, terrorism, nuclear weapons proliferation, etc.?**

Binding Energy per Nucleon And Methods of Tapping It



Alpha Decay



Binding energy prevents emission of other light nuclei or individual nucleons. Tunneling probability is too low for heavier nuclei.

$$\frac{1}{\tau_{1/2}} \propto \left[\begin{array}{c}\text{Probability}\\ \text{that } \alpha \text{ forms}\\ \text{in nucleus}\end{array}\right]\left[\begin{array}{c}\text{Frequency with}\\ \text{which } \alpha \text{ hits}\\ \text{potential barrier}\end{array}\right]\left[\begin{array}{c}\text{Probability}\\ \text{of tunneling}\\ \text{through barrier}\end{array}\right]$$

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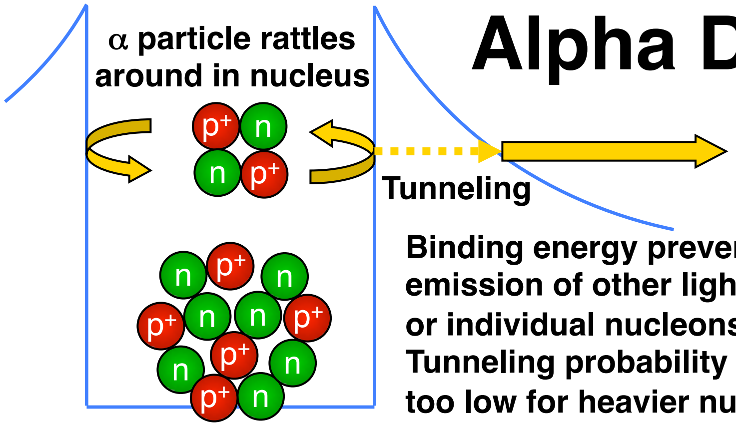

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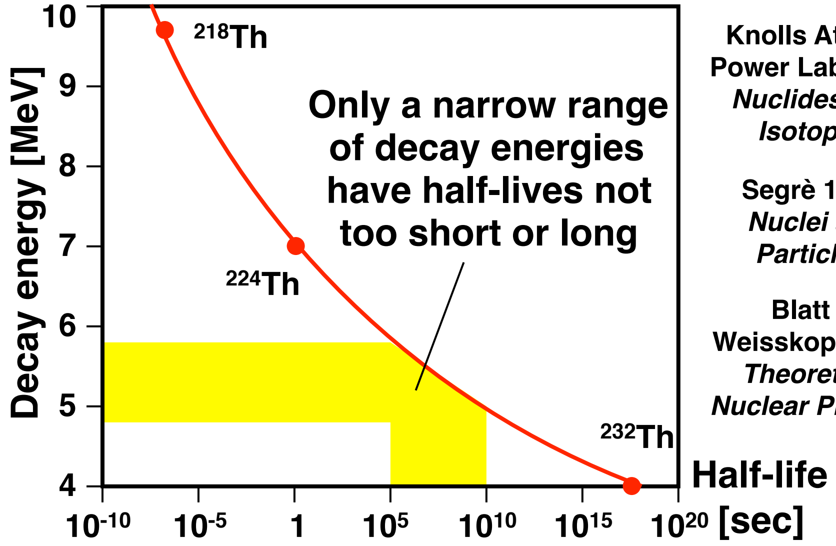

Knolls Atomic Power Lab 2010, *Nuclides and Isotopes*.

Segrè 1977, *Nuclei and Particles*.

Blatt & Weisskopf 1952, *Theoretical Nuclear Physics*.

Some α emitters

Nucleus	Energy	Half-life	Initial power
^{210}Po	5.3 MeV	136 days	141 W/g
^{242}Cm	6.1 MeV	163 days	120 W/g
^{244}Cm	5.8 MeV	18.1 yrs	2.84 W/g
^{238}Pu	5.5 MeV	88 yrs	0.56 W/g
^{241}Am	5.5 MeV	432 yrs	0.11 W/g

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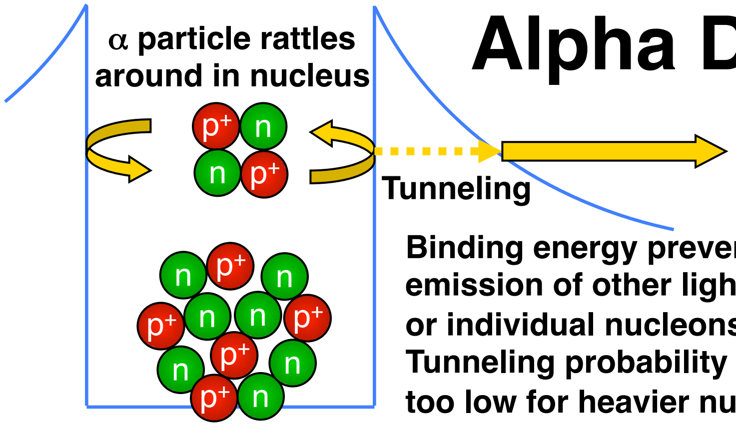

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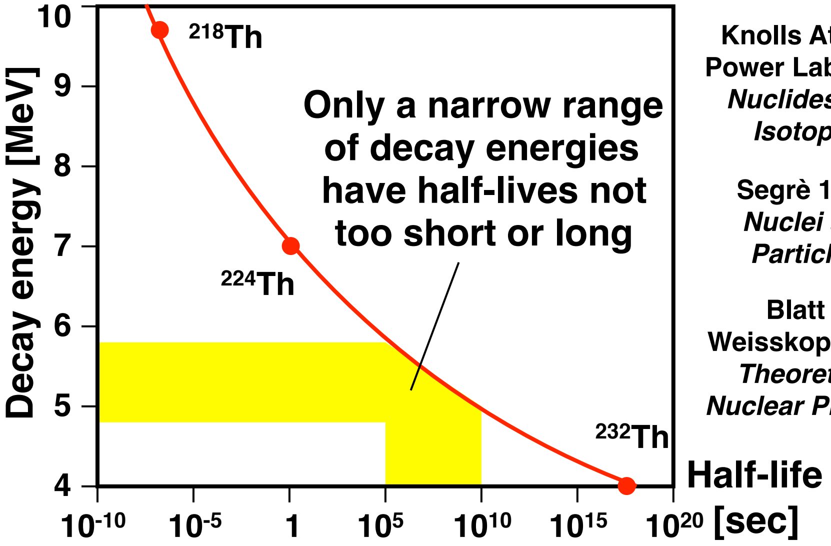

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1. Are there practical ways to use similar processes to make nuclei emit particles other than α particles (or β or γ)?

2. Are there any α emitters that are easier to produce and/or easier to use than those in the table?

3. Are there any ways to suppress the rate of α decay when it is not desired (e.g., to keep energy stored during a long interplanetary trip) and/or induce α decay when it is desired (e.g., when especially large amounts of output power are needed during an interplanetary mission)?

a. Difficult to alter potential without ~MeV input energies.

b. Nearby negative charges to decrease Coulomb barrier?

c. Nearby positive charges to increase Coulomb barrier?

d. Strong fields--electric, magnetic, electromagnetic, etc.?

e. Any practical ways to alter the shape of the nucleus?

f. Nuclear capture of a neutron, electron, antiproton, etc.?

g. Temporarily loan energy to the nucleus then recover it?

4. Are there better methods to convert the kinetic energy of the α particles and the emitting nuclei to electricity?

a. Nonthermal conversion challenging: ~μm range of alphas.

b. Increase Seebeck thermoelectric conversion efficiency?

c. Increase thermionic converter efficiency?

d. Increase thermophotovoltaic converter efficiency?

e. Get hot enough for Stirling engines, gas turbines, etc.?

f. Particle conversion and/or energy amplification by combining with other nuclear processes/materials?

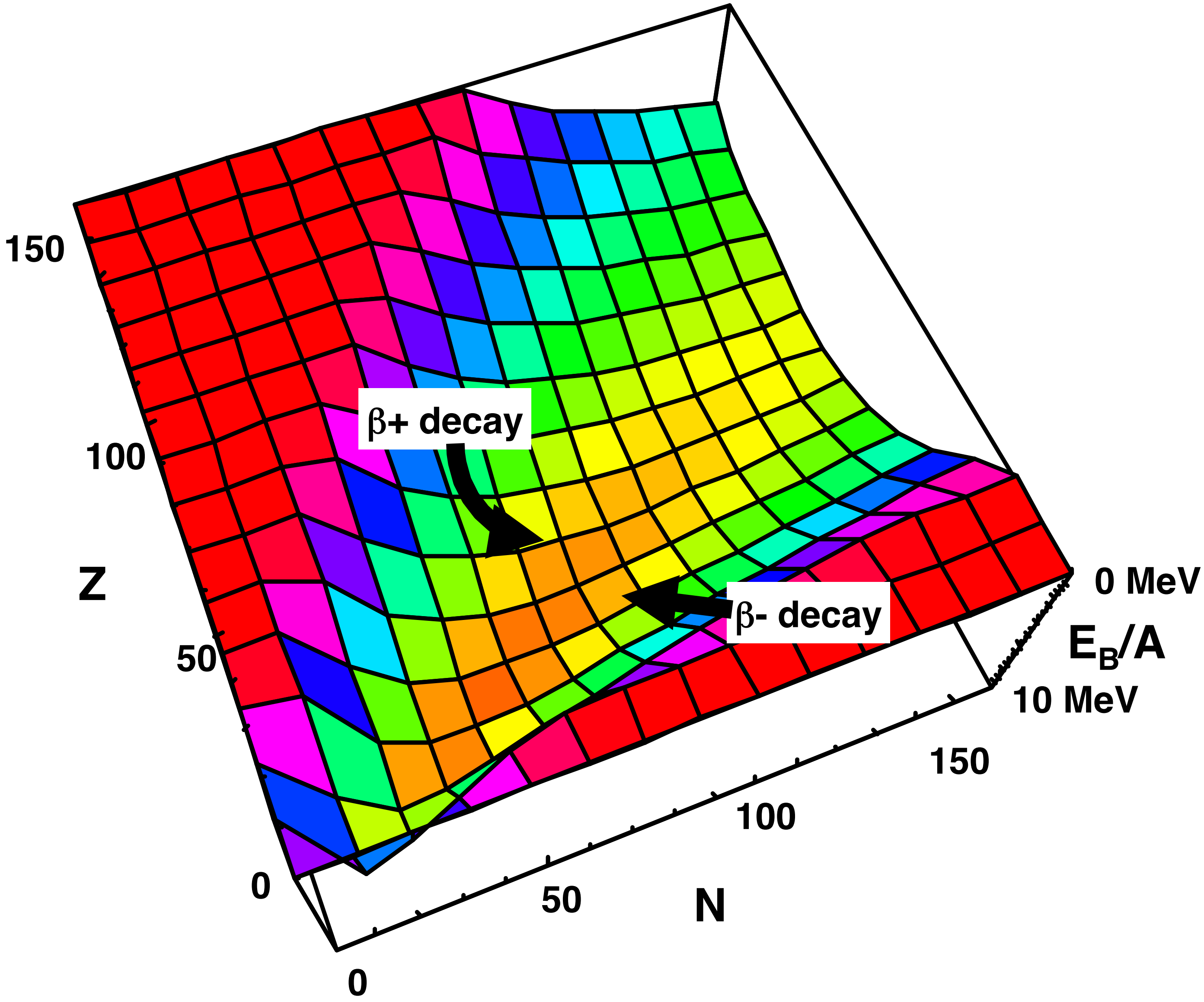
g. Electrostatic converters, inverse ion acclerators, etc.?

h. Are there other methods of conversion?

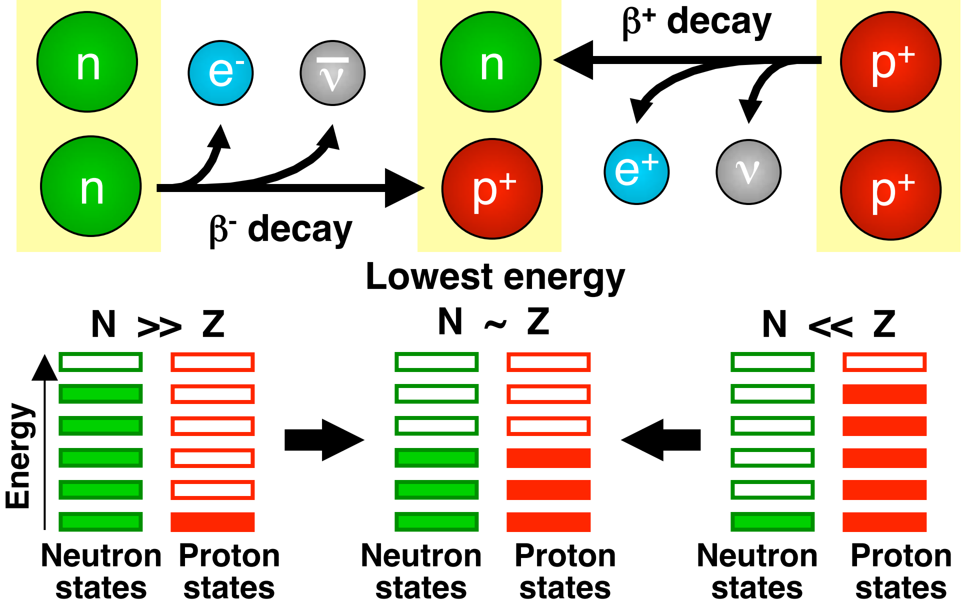
i. Multiple conversion methods to maximize efficiency?

5. Are there effective and practical ways to convert the kinetic energy of the alpha particles and the emitting nuclei to the kinetic energy of rocket exhaust?

Binding Energy per Nucleon And Methods of Tapping It



Beta Decay


n
n
e$^-$
$\bar{\nu}$
β$^-$ decay
n
p$^+$
β$^+$ decay
e$^+$
ν
p$^+$
p$^+$
Lowest energy
N >> Z
N ~ Z
N << Z
Energy
Neutron states
Proton states
Neutron states
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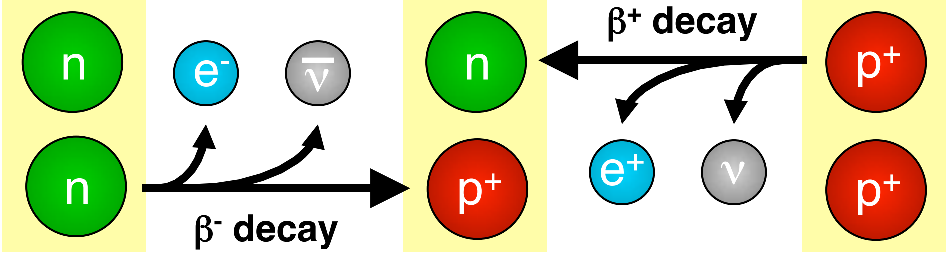
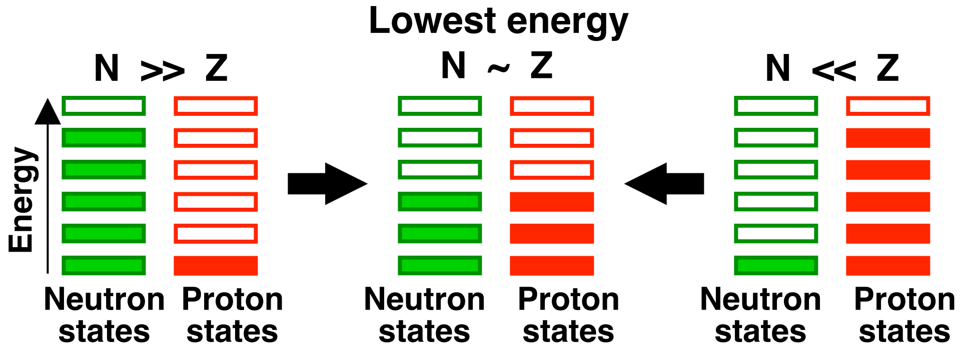
Beta Decay





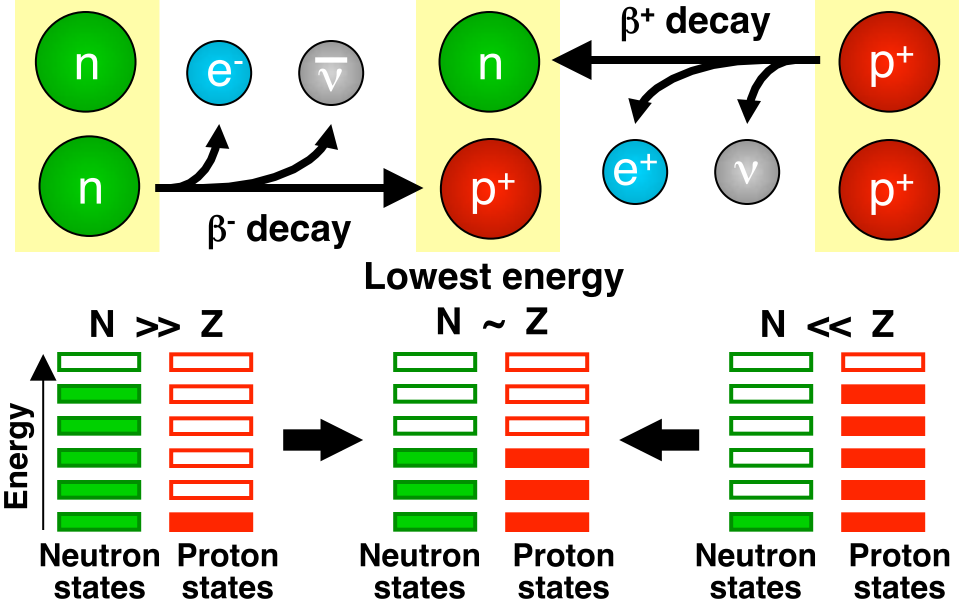
$$\tau_{1/2} \propto (10^4)^L \ (\Delta E)^{-4}$$

Some β emitters of interest

Nucleus	Energy	Half-life	Initial power
^{106}Ru	39.4 keV	1.02 yr	31.8 W/g
^{144}Ce	318 keV	285 days	25.5 W/g
^{60}Co	318 keV	5.3 yr	17.5 W/g
^{170}Tm	968 keV	129 days	11.9 W/g
^{90}Sr	546 keV	29.1 yr	0.92 W/g
^{85}Kr	687 keV	10.7 yr	0.59 W/g
^{137}Cs	514 keV	30.2 yr	0.43 W/g
^{147}Pm	224 keV	2.62 yr	0.34 W/g
^{3}H	18.6 keV	12.3 yr	0.33 W/g

Initial powers include daughter radiations: Knolls Atomic Power Lab 2010, Nuclides and Isotopes: Chart of the Nuclides. Blatt & Weisskopf 1952, Theoretical Nuclear Physics. Segrè 1977, Nuclei and Particles. DeShalit & Feshbach 1974, Theoretical Nuclear Physics.

Beta Decay



$$\tau_{1/2} \propto (10^4)^L \ (\Delta E)^{-4}$$

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β emitters with large decay energies ΔE have short half-lives unless decay requires a large emitted angular momentum L.

1. Are there any β emitters that are easier to produce and/or easier to use than those in the table?

2. Are there any ways to suppress the rate of β decay when it is not desired (e.g., to keep energy stored during a long interplanetary trip) and/or induce β decay when it is desired (e.g., when especially large amounts of output power are needed during an interplanetary mission)?

a. The β decay rate is 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.

b. Could nuclear angular momentum be altered enough to (temporarily) increase or decrease the β decay rate?

c. Could sufficiently strong electric, magnetic, electromagnetic, and/or other fields perturb nuclear states enough to (temporarily) increase/decrease the β decay rate?

d. Could the capture of a neutron, electron, antiproton, or other particle by the nucleus increase the β decay rate?

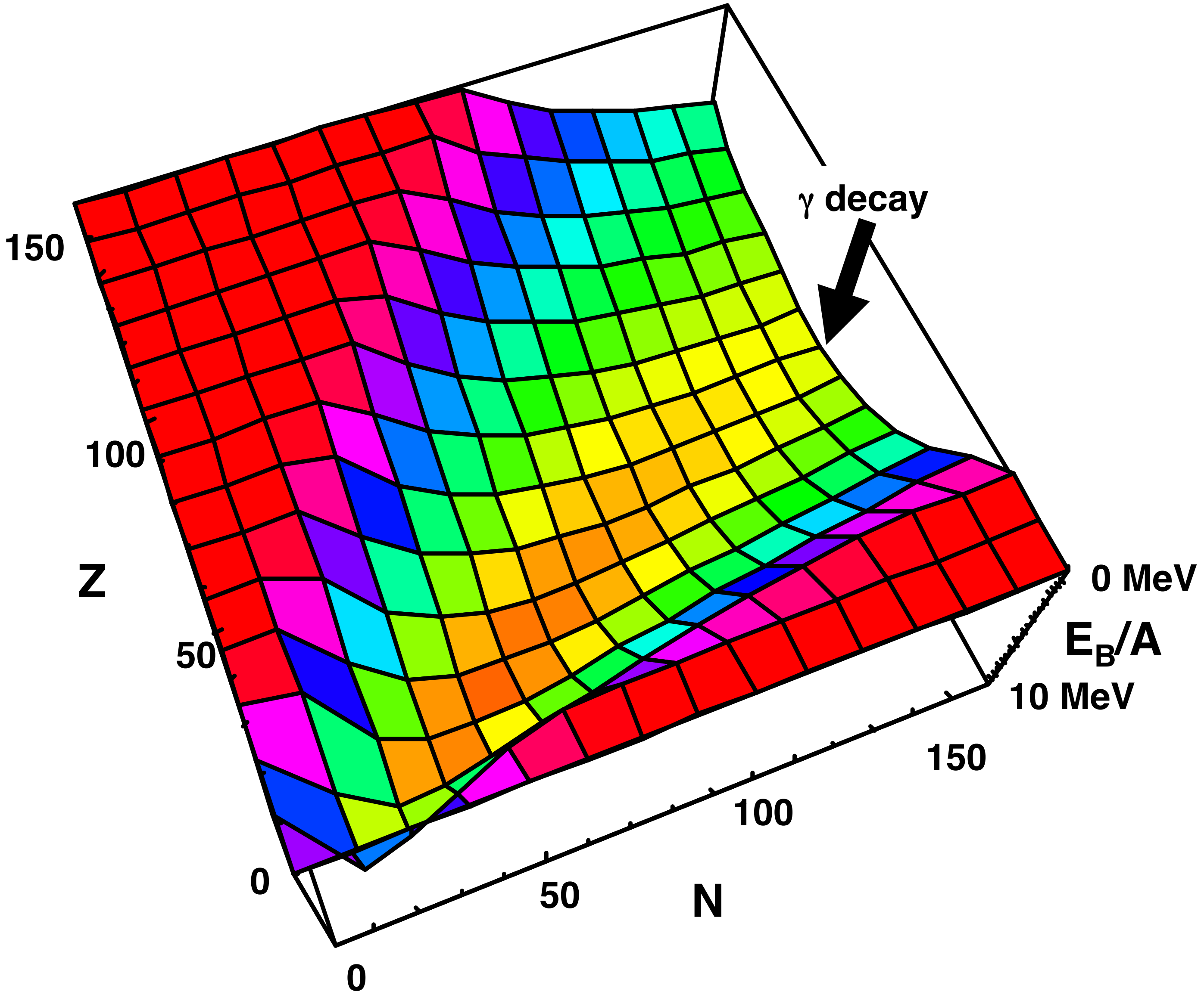
e. Could the β decay rate be increased by adding enough energy to the nucleus (via gamma rays, neutrons, or other means), then efficiently extracting that energy (plus the usual β decay energy) from the resulting β particle?

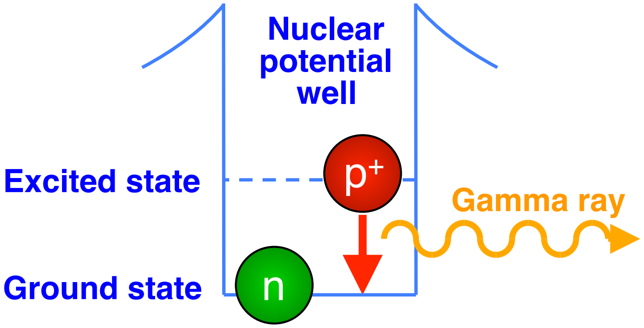
3. Are there better methods to convert the energy of the β particles to electricity?

a. The ~mm range of β particles in solids makes it quite difficult, but not necessarily impossible, to use anything other than some sort of thermal energy conversion process (usually with low conversion efficiencies).

b. See previous slide for some research directions that are applicable to β decay as well as α decay.

Binding Energy per Nucleon And Methods of Tapping It

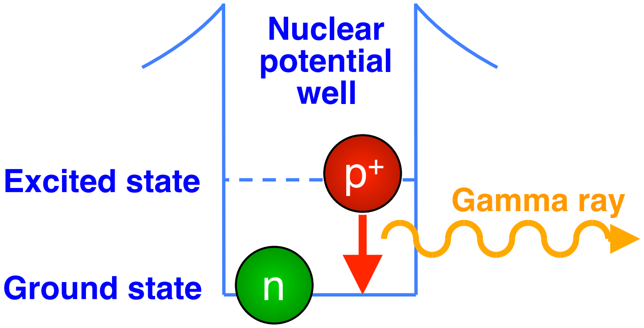




Gamma Decay

$$\tau_{1/2} \propto (10^5)^{\Delta J} (\Delta E)^{-(2\Delta J + 1)}$$

Isomers with large decay energies ΔE have very short half-lives unless the decay requires a large nuclear spin change ΔJ



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Nucleus	Energy	ΔJ	Half-life
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^{180}Ta	77.1 keV	8	$>2 \times 10^{16}$ yr
^{177}Lu	970 keV	8	160.4 d
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^{108}Ag	109 keV	5	418 yr
^{125}Te	145 keV	5	57 days
^{242}Am	48.6 keV	4	141 yr
^{93}Nb	30.7 keV	4	16.1 yr
^{99}Tc	143 keV	4	6 hr
^{58}Co	25.0 keV	3	9.0 hr
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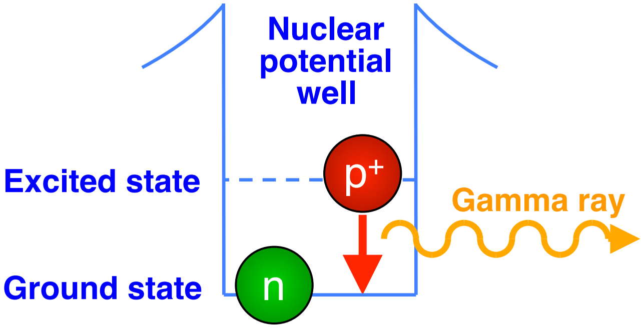
Baldwin et al 1981, Reviews of Modern Physics 53:687. Baldwin & Solem 1997, Reviews of Modern Physics 69:1085. Balko et al 1988, Gamma-Ray Lasers. Becker 2006. AIP Proceedings 819:1:396. Bellows 2007, www.damninteresting.com/half-science-and-hafnium-bombs. Brookhaven National Lab 2019, Nuclear Wallet Cards. Collins et al 1988, Physical Review C 37:5:2267. Collins et al 1999, Physical Review Letters 82:4:695. Collins et al 2000, Physical Review C 61:5:054305. Collins et al 2001, Hyperfine Interactions 135:51. Collins et al 2005, Laser Physics Letters 2:3:162. Gsponer & Hurni 2009, Physical Principles of Thermonuclear Explosives. Hahn 1921, Naturwissenschaften 9:5:84. Hartouni et al 2008, LLNL-TR-407631. Jain et al 2021, Nuclear Isomers: A Primer. Killus 2007, unintentional-irony.blogspot.com/2007/01/gamma-laser.html. Lewis et al 1997, JASON Report JSR-97-110. Litz & Merkel 2004, www.dtic.mil/dtic/tr/fulltext/u2/a433348.pdf. Pereira et al 2007, Laser Physics 17:6:874. Poppe et al 1992, UCRL-JC-109928-Rev.1. Rivlin 2007, Quantum Electronics 37:8:723. Schwarzschild 2004, Physics Today 57:5:21. Walker & Carroll 2007, Nuclear Physics News 17:2:11. Walker & Dracoulis 1999, Nature 399:35. Weinberger 2006, Imaginary Weapons. Zadernovsky & Carroll 2002, Hyperfine Interactions 143:153. Zimmerman 2007, APS News 16:6:8.



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^{163}Ho	298 keV	3	1.1 sec

1. Are there any isomers/γ emitters that are easier to produce and/or easier to use than those in the table?

2. What are the most efficient ways to produce isomers of interest?

3. Are there any ways to suppress the rate of γ decay when it is not desired and/or induce γ decay when it is desired?

a. The γ decay rate is 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.

b. Could internal conversion, internal pair creation, and other atomic electron processes be useful?

c. Could nuclear angular momentum be altered enough to (temporarily) increase or decrease the γ decay rate?

d. Could sufficiently strong electric, magnetic, electromagnetic, and/or other fields perturb nuclear states enough to (temporarily) increase or decrease the γ decay rate?

e. Could the capture of a neutron, electron, antiproton, or other particle by the nucleus increase the γ decay rate?

f. Could the γ decay rate be increased by adding enough energy to the nucleus (via γ, neutrons, or other means), then efficiently extracting that energy (plus the usual γ decay energy) from the resulting decay?

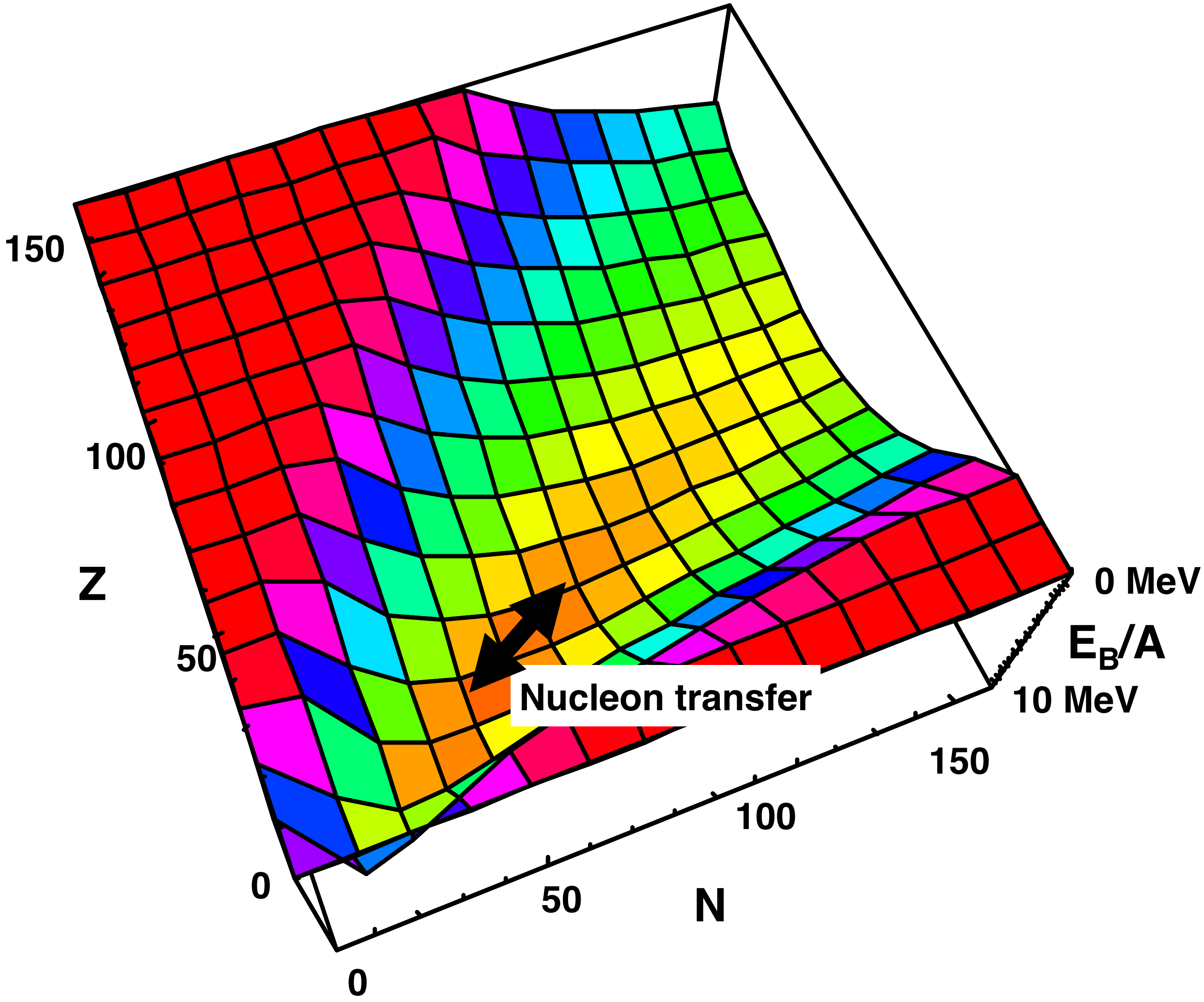
g. Could γ from one isomer decay induce the decay of other isomers?

4. Are there efficient methods to convert the energy of γ to electricity (inverse Compton effect, etc.)?

5. Could isomers be used to create a practical γ laser?

Baldwin et al 1981, Reviews of Modern Physics 53:687. Baldwin & Solem 1997, Reviews of Modern Physics 69:1085. Balko et al 1988, Gamma-Ray Lasers. Becker 2006. AIP Proceedings 819:1:396. Bellows 2007, www.damninteresting.com/half-science-and-hafnium-bombs. Brookhaven National Lab 2019, Nuclear Wallet Cards. Collins et al 1988, Physical Review C 37:5:2267. Collins et al 1999, Physical Review Letters 82:4:695. Collins et al 2000, Physical Review C 61:5:054305. Collins et al 2001, Hyperfine Interactions 135:51. Collins et al 2005, Laser Physics Letters 2:3:162. Gsponer & Hurni 2009, Physical Principles of Thermonuclear Explosives. Hahn 1921, Naturwissenschaften 9:5:84. Hartouni et al 2008, LLNL-TR-407631. Jain et al 2021, Nuclear Isomers: A Primer. Killus 2007, unintentional-irony.blogspot.com/2007/01/gamma-laser.html. Lewis et al 1997, JASON Report JSR-97-110. Litz & Merkel 2004, www.dtic.mil/dtic/tr/fulltext/u2/a433348.pdf. Pereira et al 2007, Laser Physics 17:6:874. Poppe et al 1992, UCRL-JC-109928-Rev.1. Rivlin 2007, Quantum Electronics 37:8:723. Schwarzschild 2004, Physics Today 57:5:21. Walker & Carroll 2007, Nuclear Physics News 17:2:11. Walker & Dracoulis 1999, Nature 399:35. Weinberger 2006, Imaginary Weapons. Zadernovsky & Carroll 2002, Hyperfine Interactions 143:153. Zimmerman 2007, APS News 16:6:8.

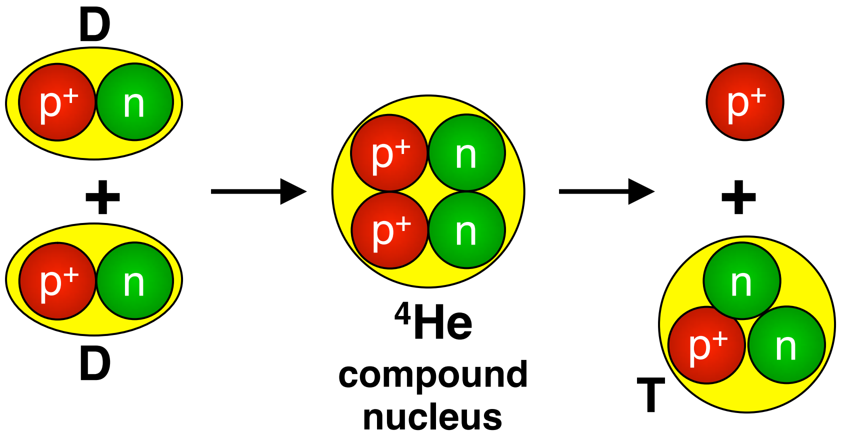
Binding Energy per Nucleon And Methods of Tapping It



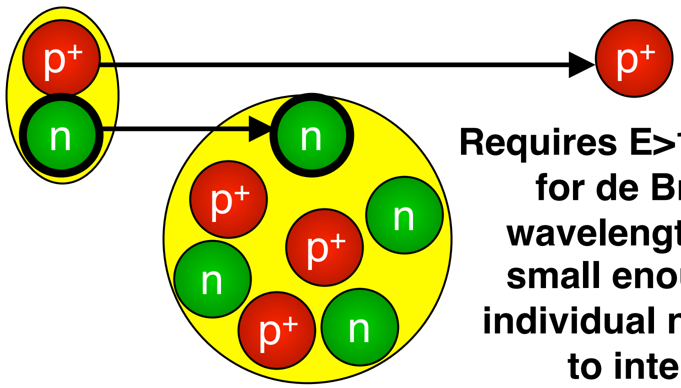
Nucleon Transfer Between Nuclei

Nuclei contact each other

Temporarily form a compound nucleus —that is just fusion:



Do not form a compound nucleus —that is a direct reaction (stripping or pickup):



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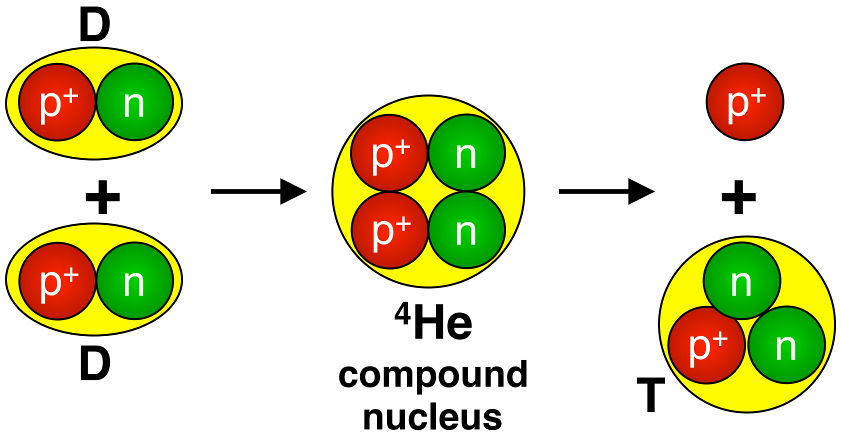

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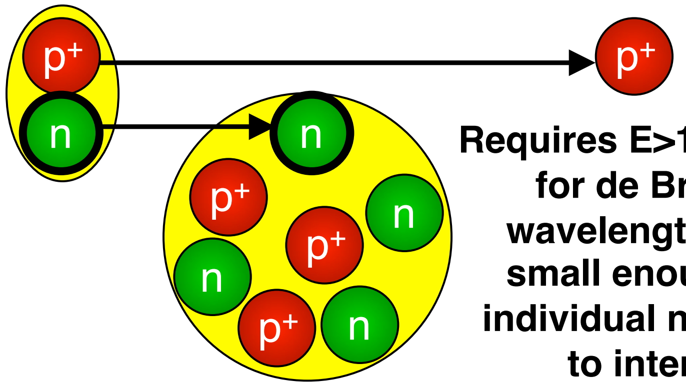

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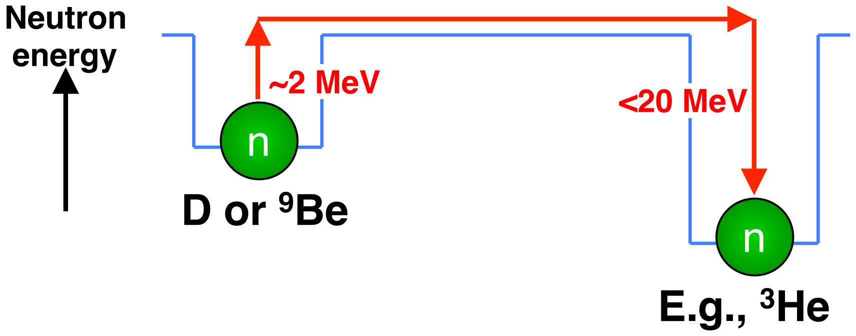
Nuclei not in contact



Much easier to transfer neutrons than protons—no Coulomb barrier

Difficult to supply input & remove output energy without fission

Proposed magical neutron transfer methods (no evidence so far):

- **Meshuganon/meshugatron particle**
- **Polyneutrons**
- **Coherent neutron quantum states**
- **Lattice vibration energy in solids**

Barnhart 2009, Defense Intelligence Agency Report DIA-08-0911-003. Berlinguette et al 2019, *Nature* 570:45. Hagelstein et al 2004, New Physical Effects in Metal Deuterides, www.lenr-canr.org. Hagelstein & Chaudhary 2015, *Current Science* 108:4:507. Huizenga 1993, *Cold Fusion: The Scientific Fiasco of the Century.* Landis & Huizenga 1989, Report DOE/S-0073, www.osti.gov/servlets/purl/5144772. Storms 2012, A Student's Guide to Cold Fusion, www.lenr-canr.org.

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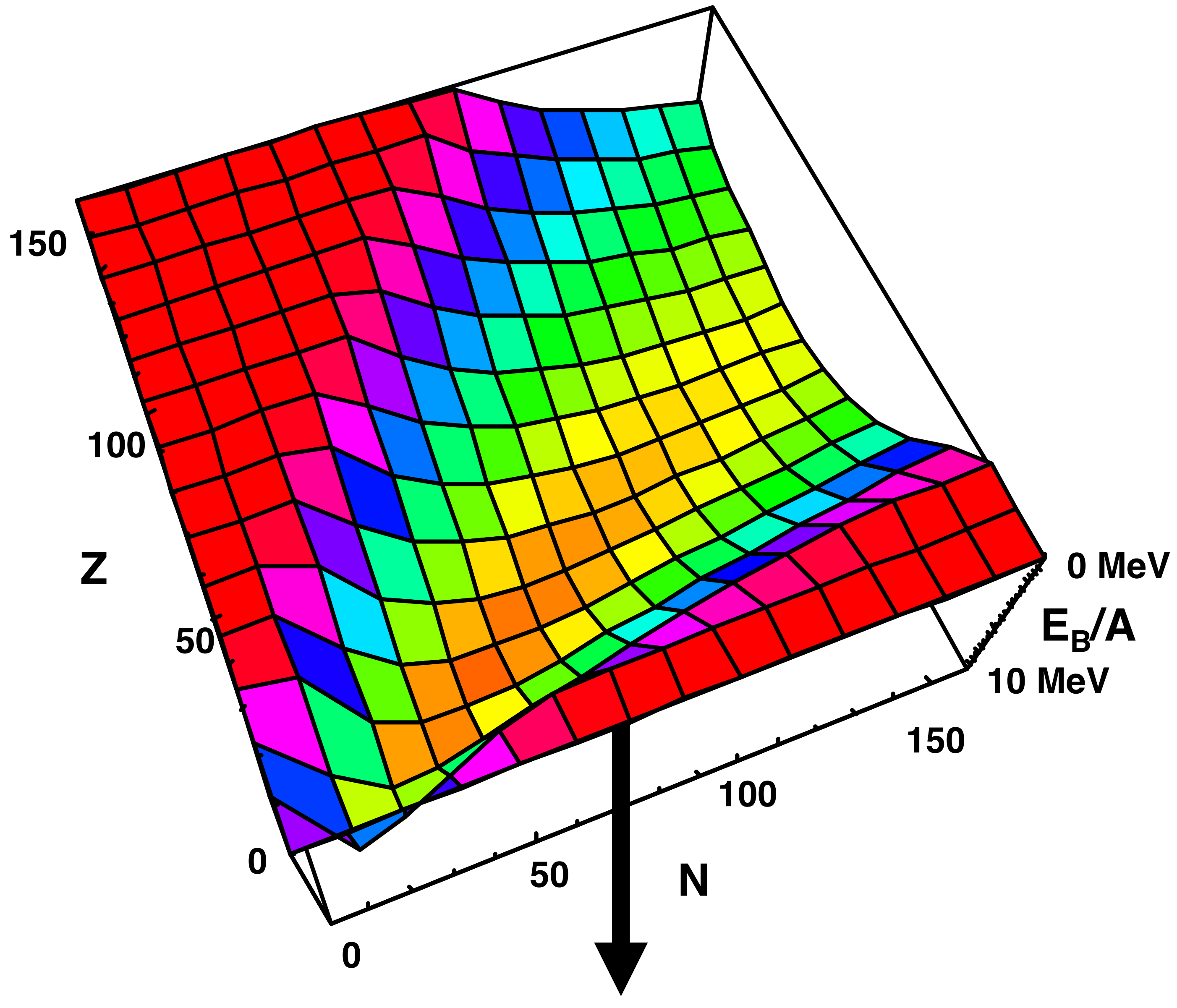

Gravitational collapse

Gravitational Collapse

Extract energy from mass falling into black hole (Schwarzschild radius $R_s=2GM/c^2$)

Back-of-the-envelope Newtonian calculation of the total energy of a mass m in a circular orbit with radius r and velocity $v = (GM/r)^{1/2}$:

$$E = mc^2 + 0.5mv^2 - (GMm/r)$$

$$= mc^2 - (GMm)/(2r)$$

$$= mc^2\,[1 - (R_s)/(4r)]$$

Convert up to $(R_s)/(4r)$ of infalling matter's rest mass to energy.

For closest stable orbit of nonrotating black hole, $r = 3R_s$:
Convert ~8% (actually 6% from more detailed calculations).

For closest stable orbit of maximally rotating black hole: $r = R_s/2$:
Convert ~50% (actually 42% from more detailed calculations).

For comparison, fusion converts <0.7% of rest mass to energy.

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Extract energy from the black hole itself

Nonrotating black hole:
- Hawking radiation (slow unless black hole is microscopic).

Rotating black hole—example processes:
- Penrose process for matter.
- Superradiant scattering for photons.
- Blandford-Znajek process for electromagnetic interactions.

DIY Black Hole

Implosion of Matter

Implode mass M to its Schwarzschild radius R_s:

$R = R_s = 2GM/c^2$

Before matter becomes a black hole, it becomes relativistic neutrons with a huge positive Fermi energy and a negligible negative gravitational energy.

Total energy of $N = M/m_n$ neutrons compressed to R:

$E_{compr} = N\ E_{avg\ Fermi}$

$= 0.6\ (9\pi/4)^{1/3}\ (\hbar c N^{4/3}/R)$

$= 0.6\ (9\pi/4)^{1/3}\ (\hbar c/R)\ M^{4/3}/m_n^{4/3}$

Total energy of neutrons compressed to R_s:

$E_{compr} = 0.3(9\pi/4)^{1/3}(\hbar c^3/G)M^{1/3}/m_n^{4/3}$

$= 1.2\text{x}10^{37}\ M_{kg}^{1/3}$ Joules

$= 1.2\text{x}10^{35}$ Joules for 1 mg target

Required energy is actually much larger, since only some of it goes into the implosion.

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Focused Energy

Compress a mass M within its Schwarzschild radius R_s:

$M = (R_s c^2)/(2G)$

OR

Compress an equivalent amount of energy within R_s:

$E = Mc^2 = (R_s c^4)/(2G)$

$= 6.07\text{x}10^{43}\ R_{s,\ meters}$ Joules

Diffraction limits focused size of electromagnetic waves. Best to use X- or γ-rays.

Focusing X-rays to create a black hole of atomic size (~10^{-10} meters) would require ~10^{33} Joules of X-ray energy.

(NIF is only $4\text{x}10^6$ Joules IR.)

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Particle Collider

Energy to create a black hole:

$E = Mc^2 = (R_s c^4)/(2G)$

$= 3.79\times10^{62}\ R_{s,\ meters}$ eV

Planck length—smallest size:

$L_P = (\hbar G/c^3)^{1/2}$

$= 1.62\times10^{-35}$ meters

$R_s \sim L_P$ for smallest black hole:

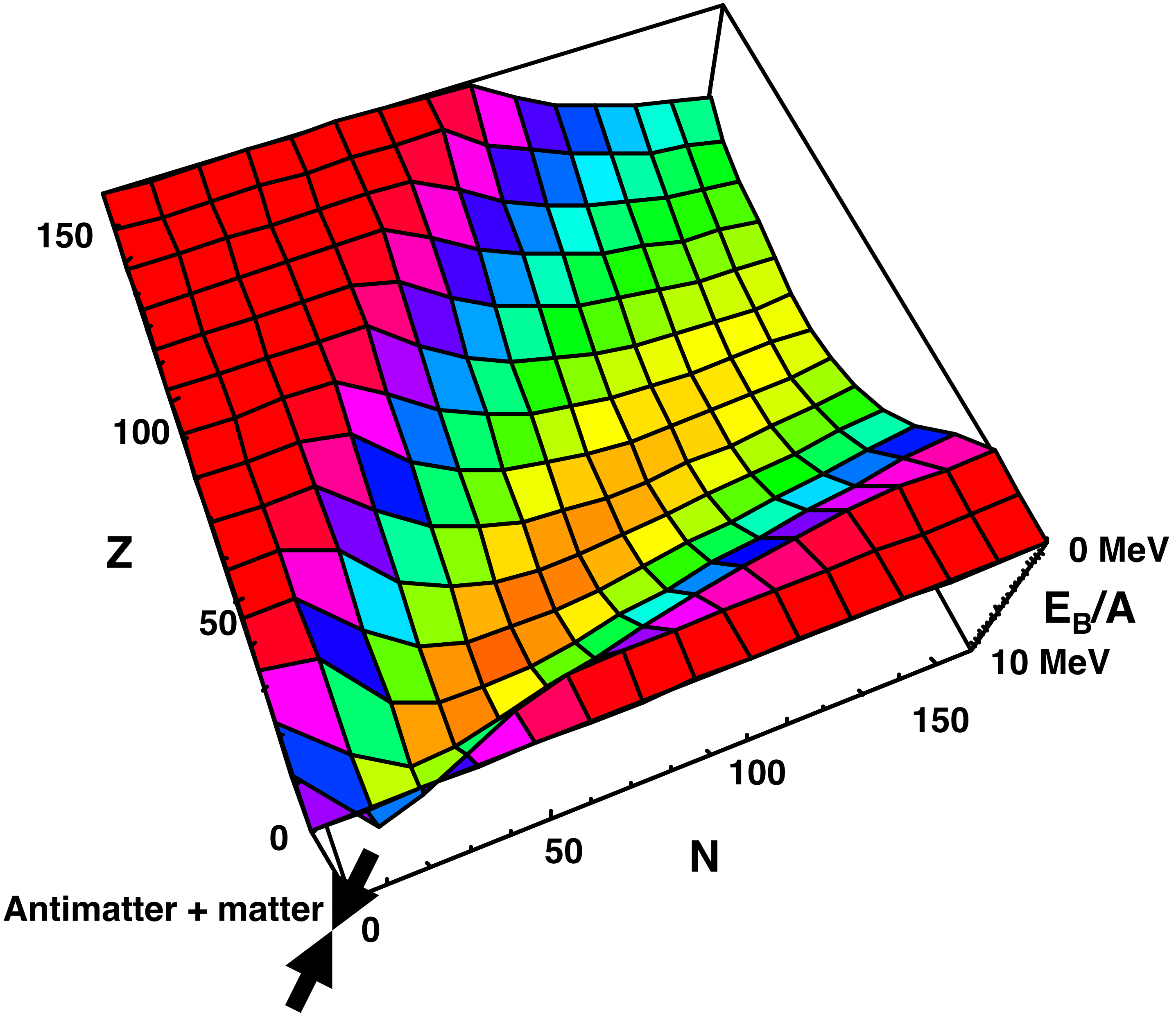
$E \sim 6\times10^{27}$ eV

(Large Hadron Collider ~ 10^{13} eV.)

Any help from new physics effects? (No signs so far.)

Tiny black holes would quickly evaporate via Hawking radiation.

Binding Energy per Nucleon
And Methods of Tapping It



Antimatter

Use

Antimatter + matter annihilation

→ 100% of mass is converted to energy
(vs. <0.7% for fusion, ~0.1% for fission)

No natural sources of antimatter

→ Useful for energy storage
but not energy production

Interstellar rocket propulsion is most important application

- Needs highest possible energy density
- Limits casualties if confinement fails

Brillouin limit on nonneutral storage:

- Rest energy density of antiparticles
< energy density of confining field

→ Little better than just storing energy in
the form of the electric/magnetic field

→ Must keep antimatter (nearly) neutral as
antiprotons + positrons (anti-hydrogen)

Energy produced as pions & γ rays

T. H. Rider 1997, *Journal of Propulsion and Power* 13:435

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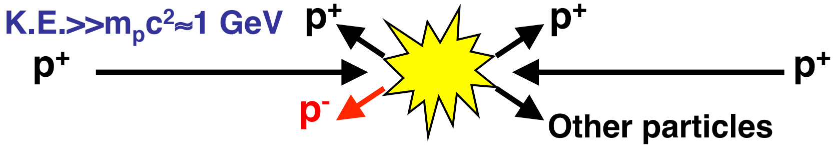
Energy produced as pions & γ rays

Production

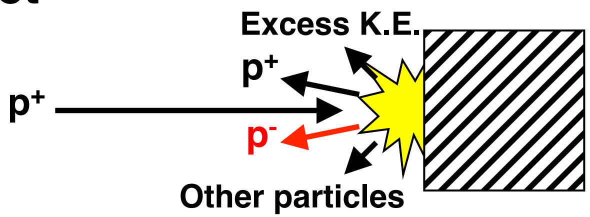
Much more difficult to make antiprotons (p^-) than positrons (e^+)

Proton (p^+) beam-beam collider:



- < 2×10^{-3} of K.E. converted into p^-
- < 10^{-5} g of p^- per year
- Colliding other particles even worse

Beam-target collider:



- > 100 g of p^- per year
- < 2×10^{-4} of K.E. converted into p^-

Converting EM field into $p^- + p^+$:

- Requires unattainable field strengths
- Still creates lots of unwanted particles

T. H. Rider 1997, *Journal of Propulsion and Power* 13:435

Binding Energy per Nucleon And Methods of Tapping It