Is There a Better Route to Fusion?

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with minor tweaks in June 2015

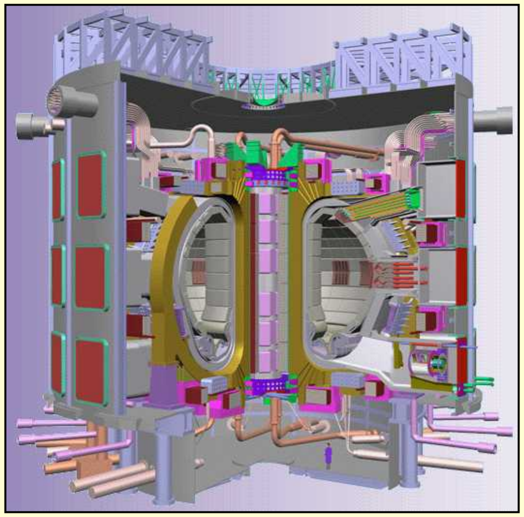
> **"Thirty-five years ago I was an expert precious-metal quartz-miner. There was an outcrop in my neighborhood that assayed $600 a ton—gold. But every fleck of gold in it was shut up tight and fast in an intractable and impersuadable base-metal shell. Acting as a Consensus, I delivered the finality 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

Three Mile Island

Current fission power approaches are not ideal

- Politically incorrect amount of radioactivity
- Conventional reactors are very expensive [>$3B each as of 2015]



ITER

Current fusion power approaches are not ideal

- Also quite radioactive and more expensive than fission reactors [>$20-50B for ITER as of 2015]
- Still decades in the future after over half a century of work

➔ We will try to “rederive” fusion 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

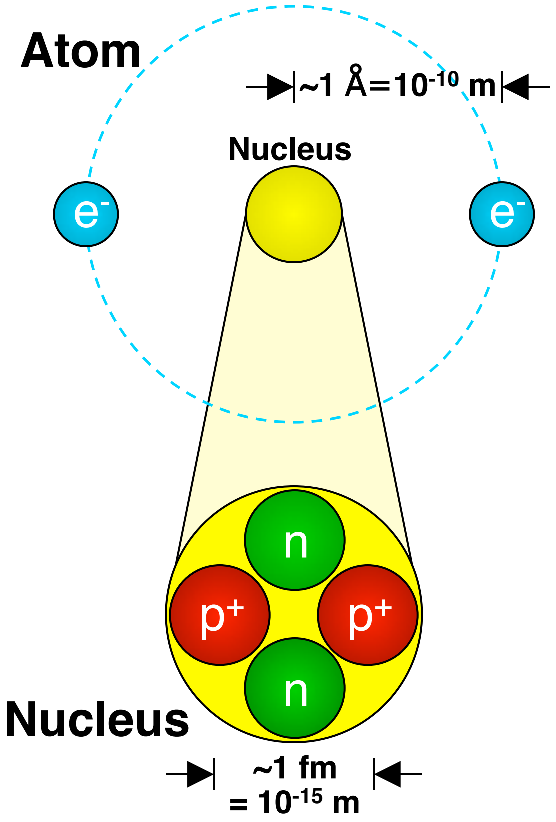
From Coulomb's law:

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

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

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

(Valid since strong force ~ Coulomb force in nucleus)



From Heisenberg uncertainty principle:

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

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

$$\frac{E_{nucl}}{E_{chem}} \sim \frac{m_e}{m_p}\left(\frac{r_{atom}}{r_{nucl}}\right)^2 \sim 10^6$$

- 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)

$$E_B = 16\,A \;-\; 17\,A^{2/3} \;-\; 0.7\,\frac{Z^2}{A^{1/3}} \;-\; 25\,\frac{(N-Z)^2}{A} \;+\; \begin{cases} 34\,A^{-3/4} & \text{even } N, Z \\ 0 & \text{odd-even} \\ -34\,A^{-3/4} & \text{odd } N, Z \end{cases} \;+ \sim \frac{A}{20}$$

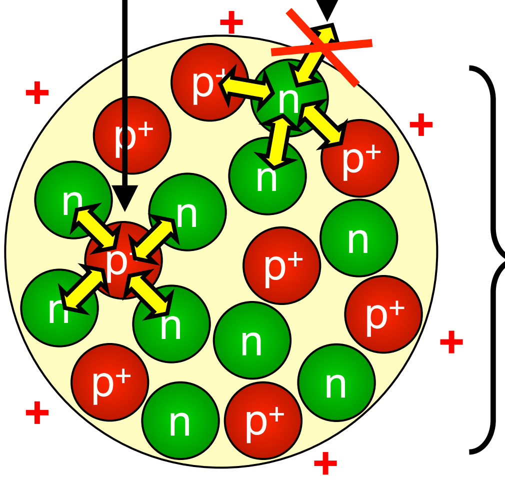
if N or Z is magic

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

Correction: nuclei at surface have fewer neighbors for binding energy

Coulomb repulsion among protons (favors N >> Z)

Favors N a bit larger than Z, especially for large nuclei



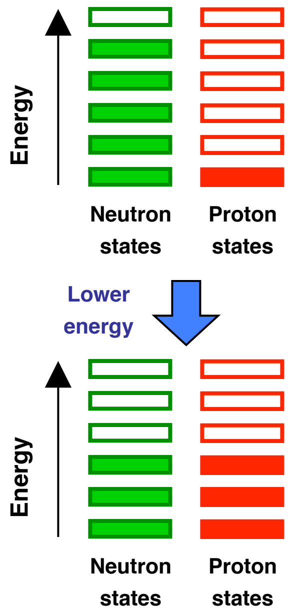
Radius ~ $A^{1/3}$

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

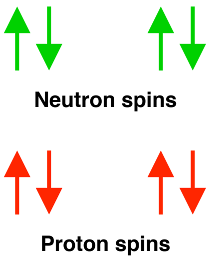
Volume ~ A

Valid for $A \geq 15$

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

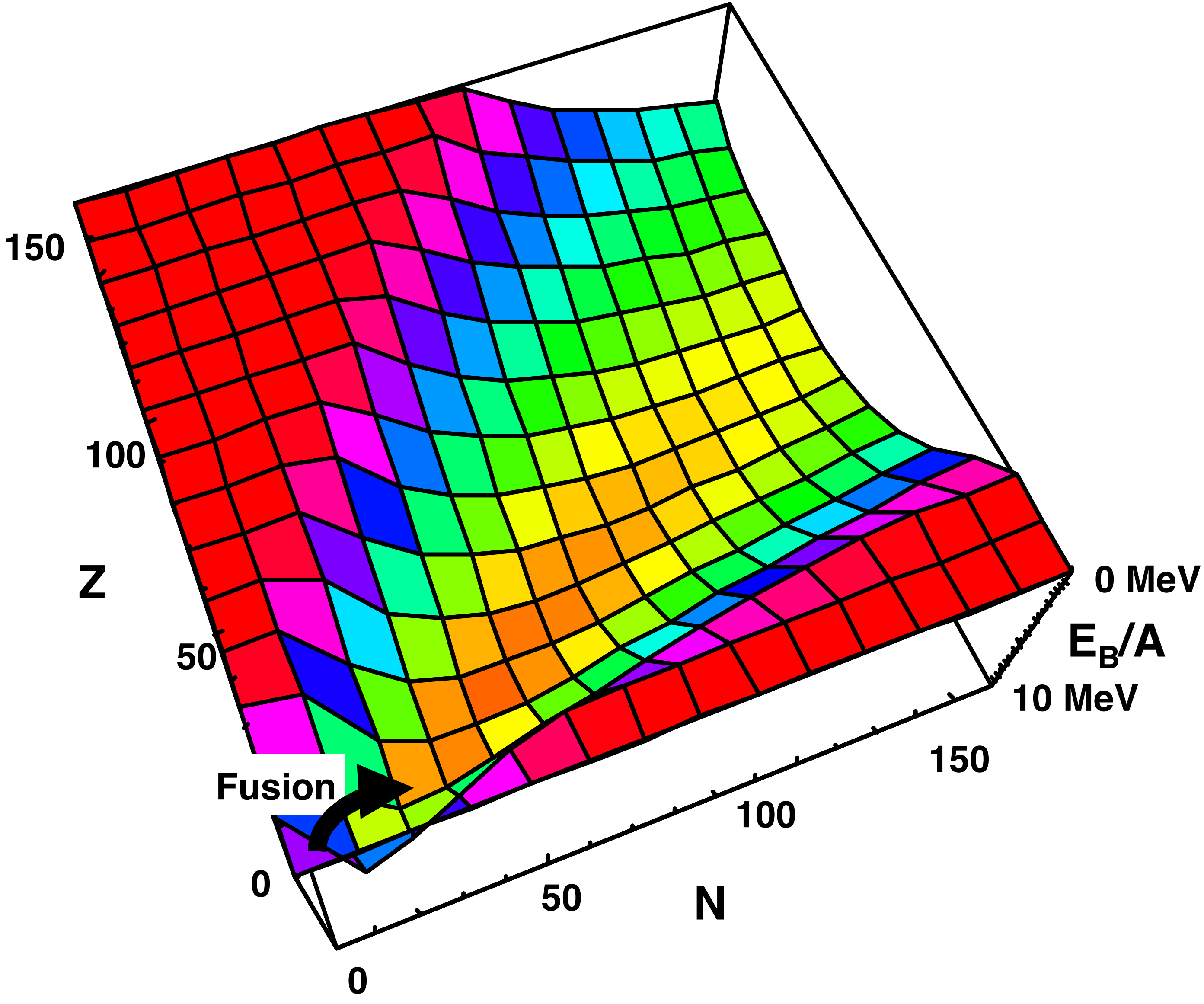


Nuclei are happiest when each nucleon is part of a pair with opposite spins



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



Possible Fusion Reactions

Input nucleus 2

Neglect:

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

Output energy Peak cross section at CM input energy
🟩 Theoretically feasible
🟨 Borderline
🟥 Not feasible

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	🟨 5.0 MeV 0.1 b at 1 MeV	🟨 16.1 MeV	🟥 16.9 MeV >0.03 b at >1 MeV	🟥 -2.1 MeV	🟥
^{7}Li	🟥 2.0 MeV 0.04 b thermal	🟥 17.3 MeV 0.006 b at 400 keV	🟨 15.1 MeV >0.5 b at >1 MeV	🟨 8.9 MeV >0.2 b at >4 MeV	🟨 11-18 MeV	🟨 8.7 MeV 0.4 b at 500 keV	🟥
^{7}Be	🟩 1.6 MeV 50,000 b thermal	🟥 0.14 MeV 2×10^{-6} b at 600 keV	🟨 16.8 MeV	🟨 10.5 MeV	🟥 11.3 MeV	🟨 7.5 MeV 0.3 b at 900 keV	🟥
^{9}Be	🟥 6.8 MeV 0.01 b thermal	🟨 2.1 MeV 0.4 b at 300 keV	🟨 7.2 MeV >0.1 b at >1 MeV	🟨 9.6 MeV >0.1 b at >2 MeV	🟥	🟨 5.7 MeV 0.3 b at 1.3 MeV	🟥
^{10}Be	🟥 Negligible	🟨	🟨	🟨	🟥	🟥	🟥
^{10}B	🟩 2.8 MeV 3800 b thermal	🟥 1.1 MeV 0.2 b at 1 MeV	🟨 9.2 MeV >0.2 b at >1 MeV	🟨	🟥	🟥	🟥
^{11}B	🟥 3.4 MeV 0.005 b thermal	🟨 8.7 MeV 0.8 b at 600 keV	🟨 13.8 MeV >0.1 b at >1 MeV	🟨 8.6 MeV	🟥	🟥	🟥
^{11}C	🟨	🟨	🟨	🟨	🟥	🟥	🟥
^{12}C	🟥 4.9 MeV 0.003 b thermal	🟥 1.9 MeV 1×10^{-4} b at 400 keV	🟨	🟨	🟥	🟥	🟥
^{13}C	🟥 8.2 MeV 0.001 b thermal	🟥 7.6 MeV 0.001 b at 500 keV	🟨	🟨	🟥	🟥	🟥
^{14}C	🟥 Negligible	🟨	🟨	🟨	🟥	🟥	🟥

$Z_1Z_2\geq8$ →

Coulomb barrier is too high ↓

$Z_1Z_2\geq7$ Coulomb barrier is too high

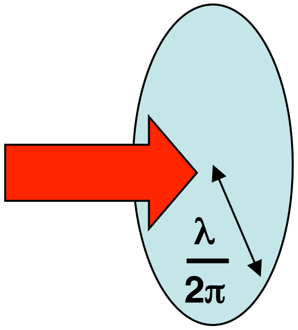
Physical Factors in Fusion Cross Section (in barns)

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

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

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

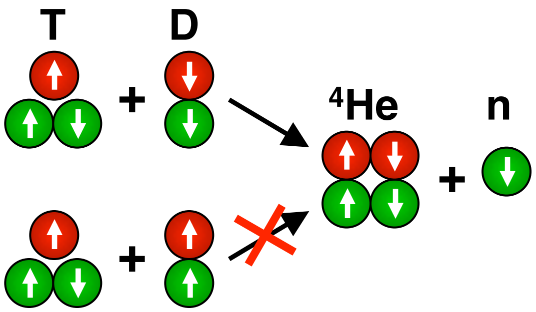
Diffraction-limited cross-sectional area $\pi\,(\lambda/2\pi)^2$ for wavefunctions of colliding nuclei



Input nuclei must have correct spins to fuse

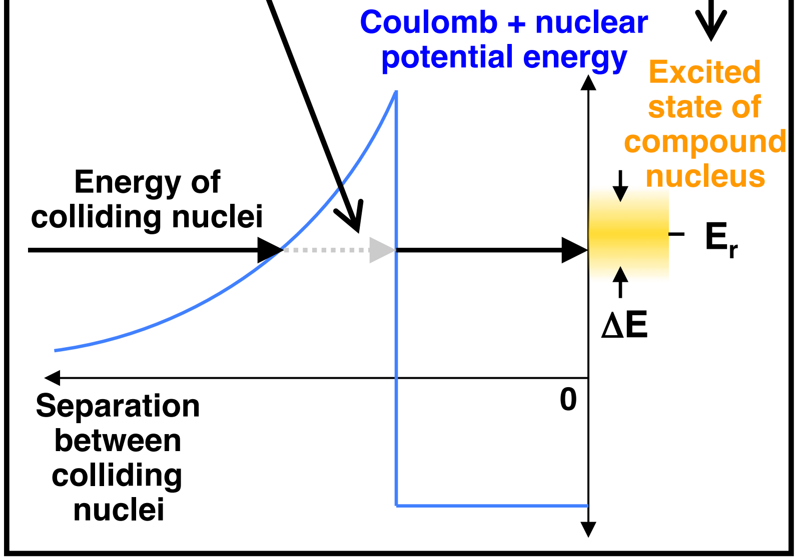
Sum over 2J+1 possible spin states of compound nucleus and average over $(2J_1+1)$ and $(2J_2+1)$ spin states of each input nucleus

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



Probability of tunneling through Coulomb barrier between nuclei

Collision energy E_{CM} must be within ~ΔE/2 of excited state energy E_r of compound nucleus



Improve Spin Polarization Factor in σ_{fus}

Need better evidence (especially experimental) for or against:

- **Potential benefits of spin-polarized nuclei**
  - Increase σ_{fus} by 50% for D+T/D+^{3}He, 50-100% for D+D, 56% for p+^{11}B [1: pp. 161-168]
  - Suppress neutron-producing D+D side reactions in D+^{3}He plasmas [1: pp. 161-168]
  - Control angular distribution of products [1: pp. 169-178 & 269-271; 2]
- **Methods of producing spin-polarized nuclei**
  - Spin-exchange optical pumping [3]
  - Cryogenic, neutral beam, and other methods [1: pp. 213-247; 2]
- **Depolarization mechanisms (two-body collisions don't affect spin [2])**
  - Interactions with first wall [4]
  - Interactions with magnetic inhomogeneities or fluctuations [2]
  - Interactions with waves [5]
  - Spin-orbit and spin-spin interactions [6]
  - Long-range three-body collisions

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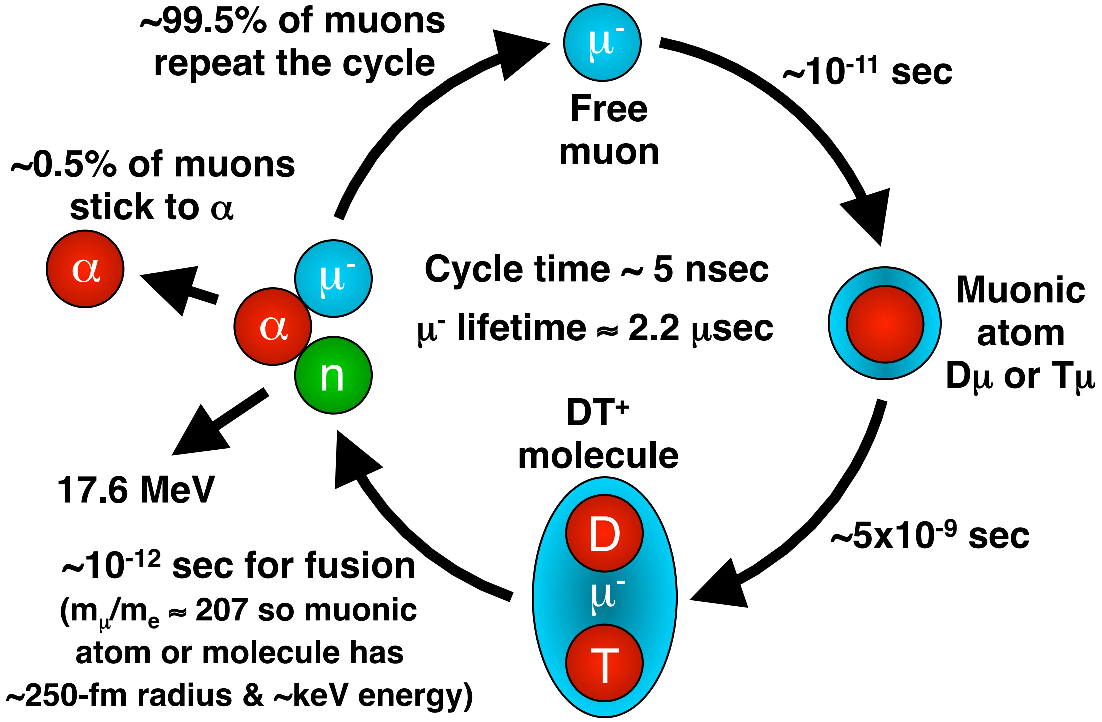
[1] Brunelli & Leotta (eds.), *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei* (Plenum Press, 1987)
[2] R. M. Kulsrud, E. J. Valeo, & S. C. Cowley, *Nuclear Fusion* 26, 1443 and *Phys. Fluids* 29, 430 (1986)
[3] S. G. Redsun *et al., Phys. Rev. A* 42, 1293 (1990); M. Poelker *et al., Phys. Rev. A* 50, 2450 (1994)
[4] H. S. Greenside, R. V. Budny, and D. E. Post, *J. Vac. Sci. Technol. A* 2, 619 (1984)
[5] B. Coppi *et al*., *Phys. Fluids* 29, 4060 (1986)
[6] W. Y. Zhang and R. Balescu, *J. Plasma Physics* 40, 199 and 215 (1988)

Improve Tunneling Factor in σ_{fus}: Muon Catalysis [1]



~99.5% of muons repeat the cycle

Free muon

~10^{-11} sec

~0.5% of muons stick to α

Cycle time ~ 5 nsec

μ^- lifetime ≈ 2.2 μsec

Muonic atom Dμ or Tμ

DT$^+$ molecule

17.6 MeV

~5×10^{-9} sec

~10^{-12} sec for fusion

($m_\mu/m_e \approx 207$ so muonic atom or molecule has ~250-fm radius & ~keV energy)

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.
≈ 1 GeV useful output per μ^-

Need unsticking methods

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

Need way to reduce cycle time [2]

Performance is much worse for reactions other than D+T

Other massive negative particles:

- Antiprotons are a loser [3]
- Other particles are harder to produce and shorter-lived than μ^-
- Large effective e^- mass or charge in solids does not help [4]

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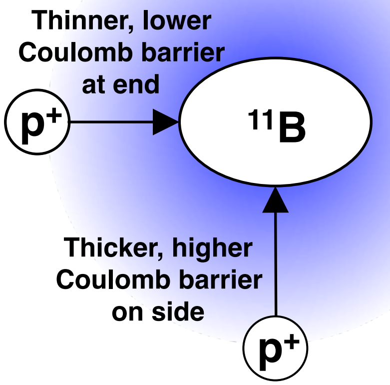
[1] Brunelli & Leotta (eds.), *Muon-Catalyzed Fusion and Fusion with Polarized Nuclei* (Plenum Press, 1987)
[2] M. C. Fujiwara *et al., Phys. Rev. Lett.* 85, 1642 (2000) only decreases the time for the *first* cycle, not later ones
[3] D. L. Morgan, L. J. Perkins, and S. W. Haney, *Hyperfine Interactions* 102, 503 (1996)
[4] J. R. Huizenga *et al*., Report DOE/S-0073 (Nov. 1989), www.newenergytimes.com/DOE1989/contents.htm

Improve Tunneling Factor in σ_{fus}: Other Methods

Shape-polarized fusion



Thinner, lower Coulomb barrier at end

Thicker, higher Coulomb barrier on side

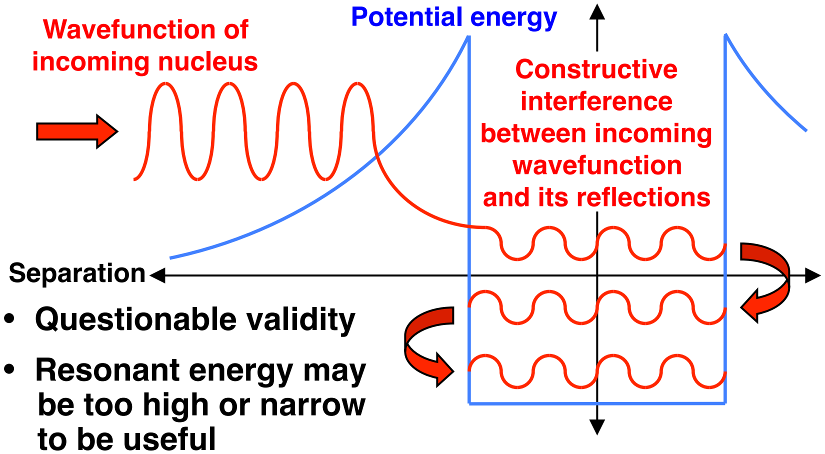
σ_{fus} for end only is ~10x larger than angle-averaged σ_{fus}

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

much faster than fusion

L.J. Perkins, *Phys. Lett. A* 236, 345 (1997)

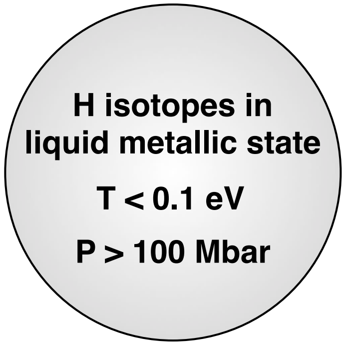
Resonant tunneling



- Questionable validity
- Resonant energy may be too high or narrow to be useful

X.Z. Li *et al., Phys. Rev. C* 61, 024610 (2000)

Liquid metallic hydrogen



H isotopes in liquid metallic state

$T < 0.1$ eV

$P > 100$ Mbar

S. Ichimaru,
Rev. Mod. Phys.
65, 255 (1993)

σ_{fus} is greatly increased by
- electron screening of Coulomb potential
- many-particle correlations among nuclear states

- Is there a better way to beat the Coulomb barrier?
- Can one show that these ideas completely cover the phase space of methods for dealing with the Coulomb barrier?
- Are there ways to improve the other two factors in σ_{fus}? (Doubtful)

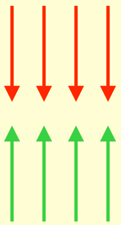
Why Ions Won't Behave

Desired property:

Why you can't have it:

What you're left with:

Ion species 1

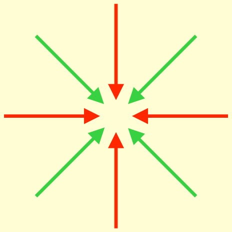


Ion species 2

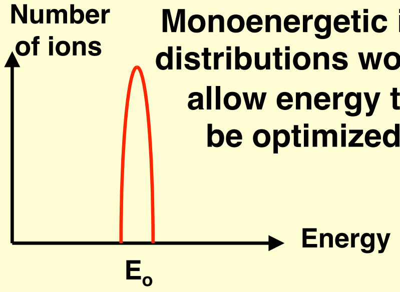
Highly anisotropic velocity distributions would allow collisions to have best CM energy

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

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



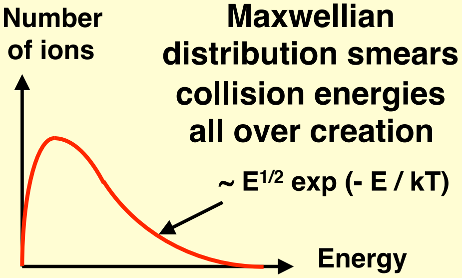
Approximately isotropic distributions collide at wide range of CM energies

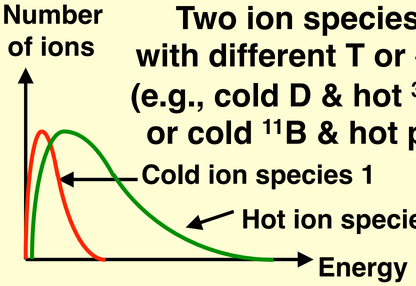


Monoenergetic ion distributions would allow energy to be optimized

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

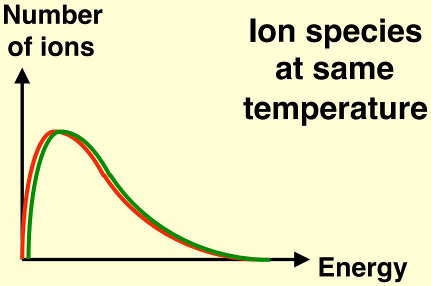
Maxwellian distribution smears collision energies all over creation





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 $\tau_{col} \ll \tau_{fus}$

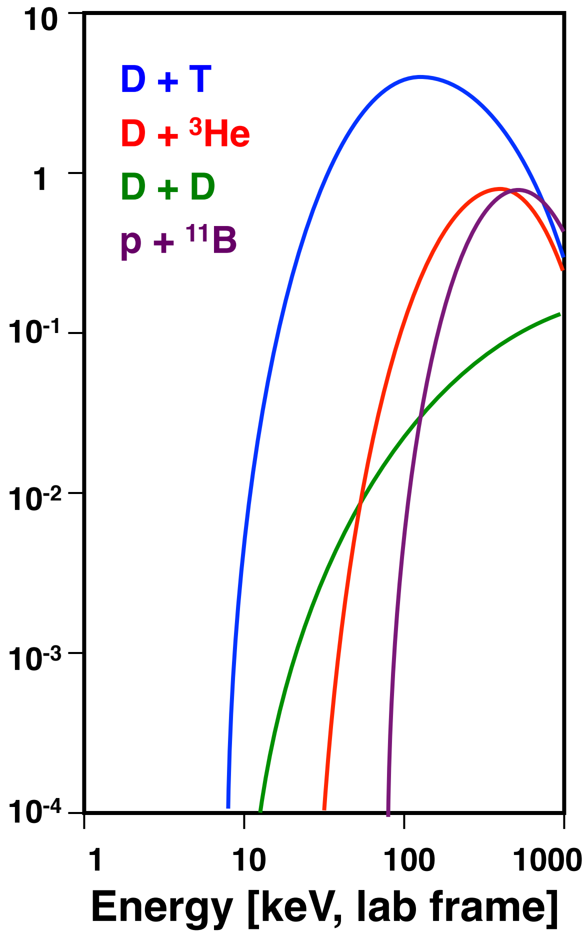


Ion species at same temperature

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

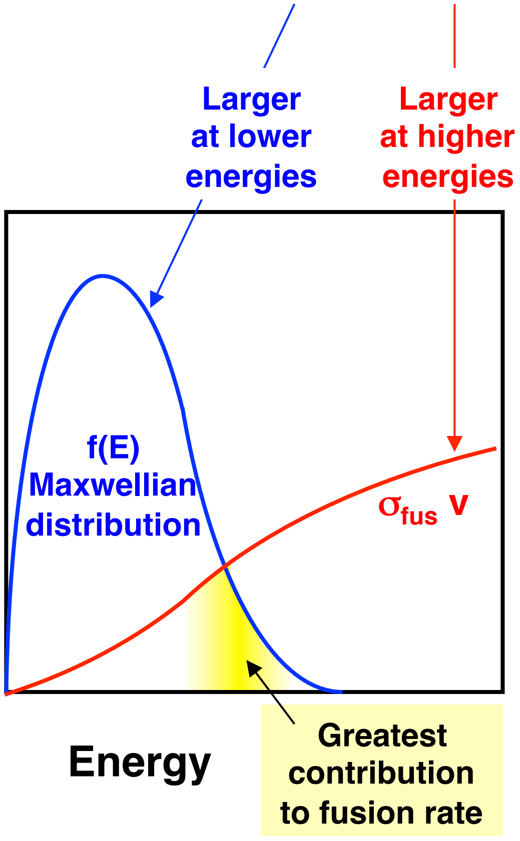
Cross Sections for Major Fusion Reactions

σ_{fus} [barns] for major reactions

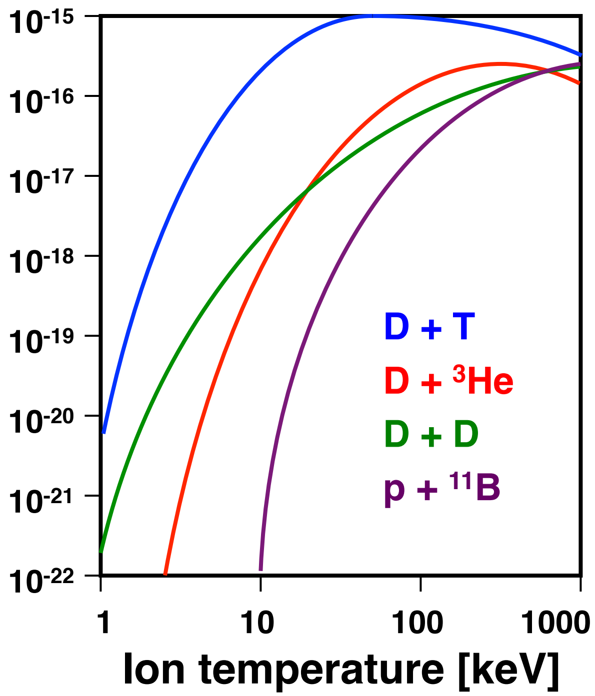


Reaction rate/volume $= \langle \sigma_{fus}\, v \rangle\, n_{i1}\, n_{i2}$

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



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



Electrons

You Can't Live Without Them

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

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

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

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

Fusion power density limited to:

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

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

Electrons must be present to reach useful fusion power densities.

You Can't Live With Them

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

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

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

If photons are confined

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

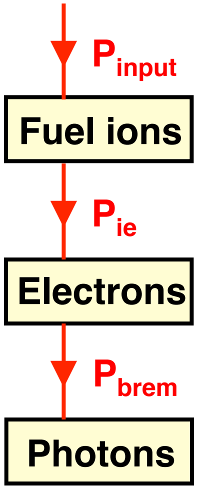
$$\frac{E_{photons}}{E_{ions}} \approx \frac{8\,\sigma_{SB}\,T^3}{3\,c\,k_B\,n_i}$$

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}

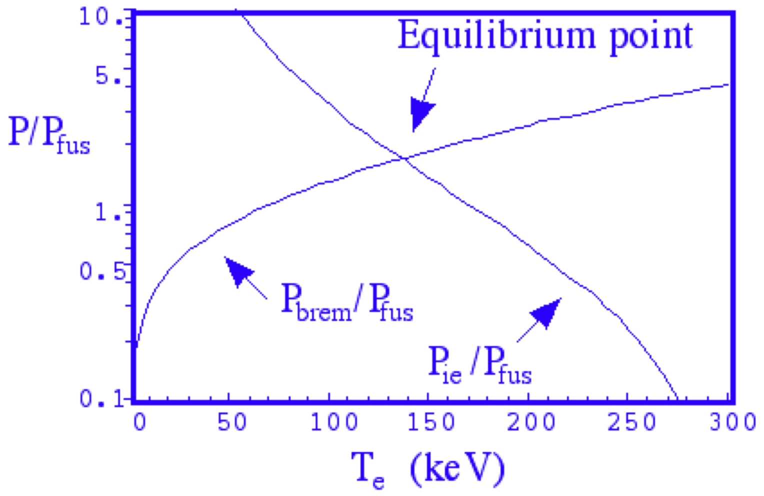
Electrons

P_{brem}

Photons

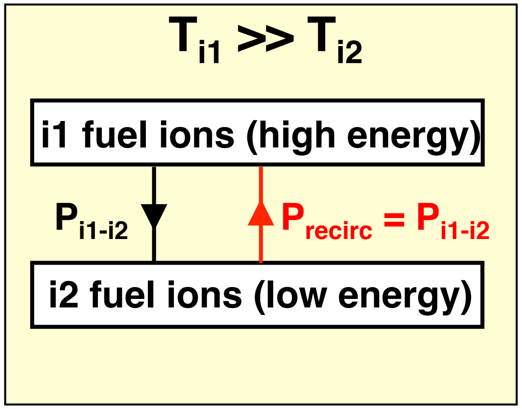
If photons escape

E.g.: 5:1 p+^{11}B with T_i=300 keV



Minimum P_{brem}/P_{fus}		
D+T	0.007	Feasible
D+^{3}He	0.19	
D+D	0.35	
^{3}He+^{3}He	1.39	Ouch
p+^{11}B	1.74	
p+^{6}Li	4.81	

Required Power to Maintain Nonequilibrium Plasma



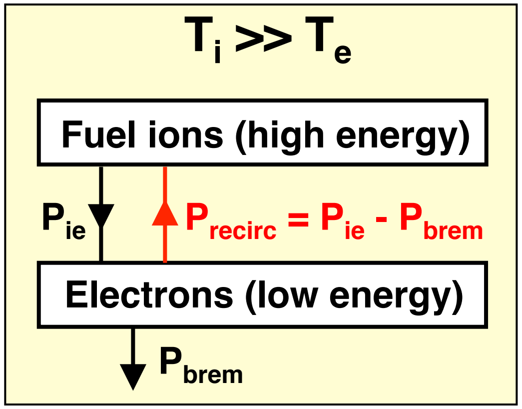
$T_{i1} \gg T_{i2}$

i1 fuel ions (high energy)

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

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

i2 fuel ions (low energy)



$T_i \gg T_e$

Fuel ions (high energy)

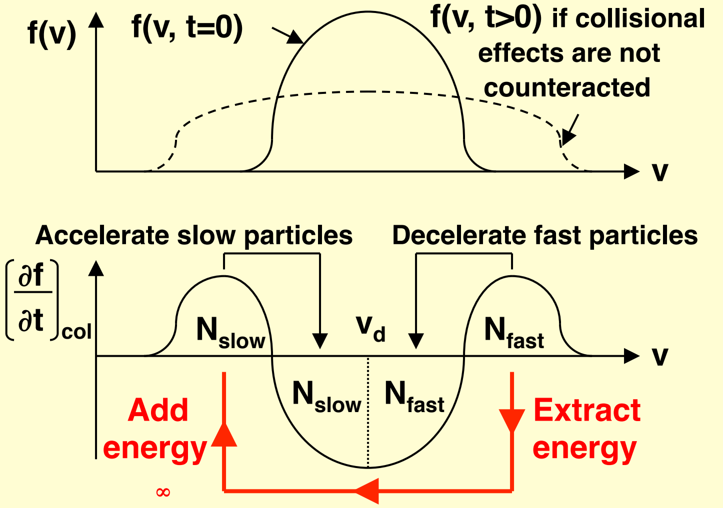
P_{ie}

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

Electrons (low energy)

P_{brem}

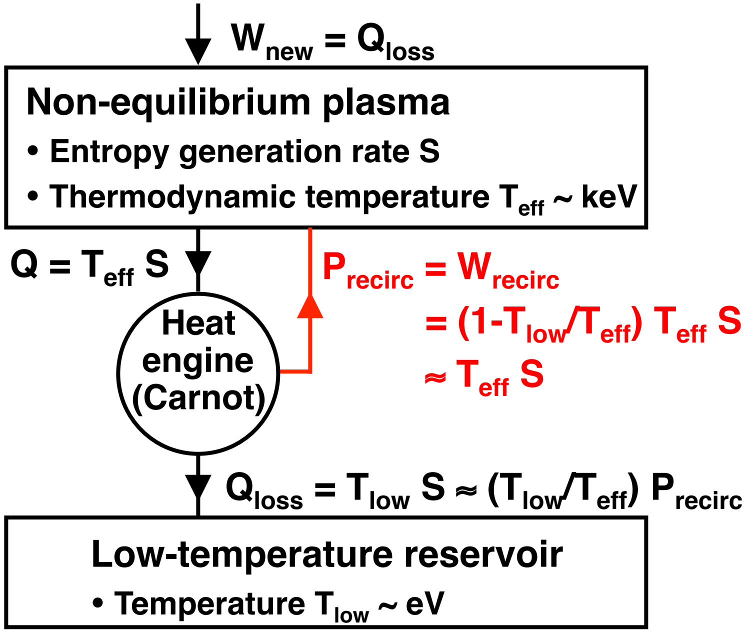
Non-Maxwellian Distribution f(v)



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

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

Idealized System for Recirculating Power to Maintain a Nonequilibrium Plasma



$W_{new} = Q_{loss}$

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

$Q = T_{eff} S$

Heat engine (Carnot)

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

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

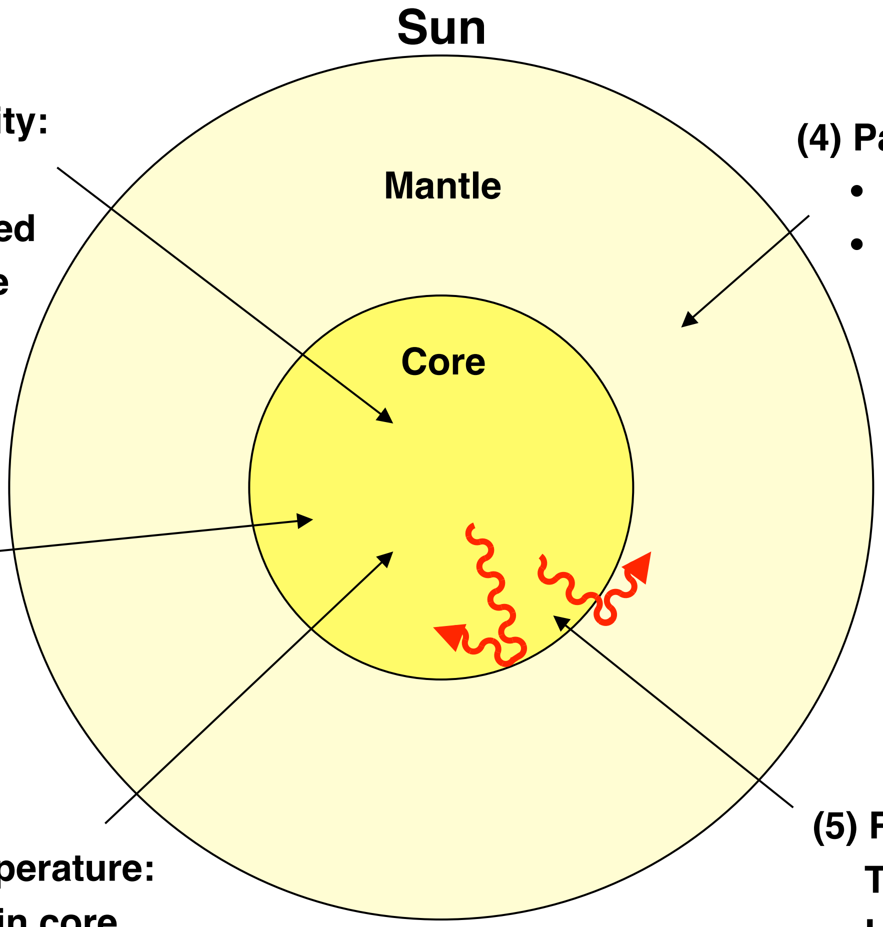
Low-temperature reservoir
- Temperature T_{low} ~ eV

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

T. H. Rider, *Phys. Plasmas* 4, 1039 (1997) and Ph.D. thesis, MIT (1995)—don't overlook Appendix 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

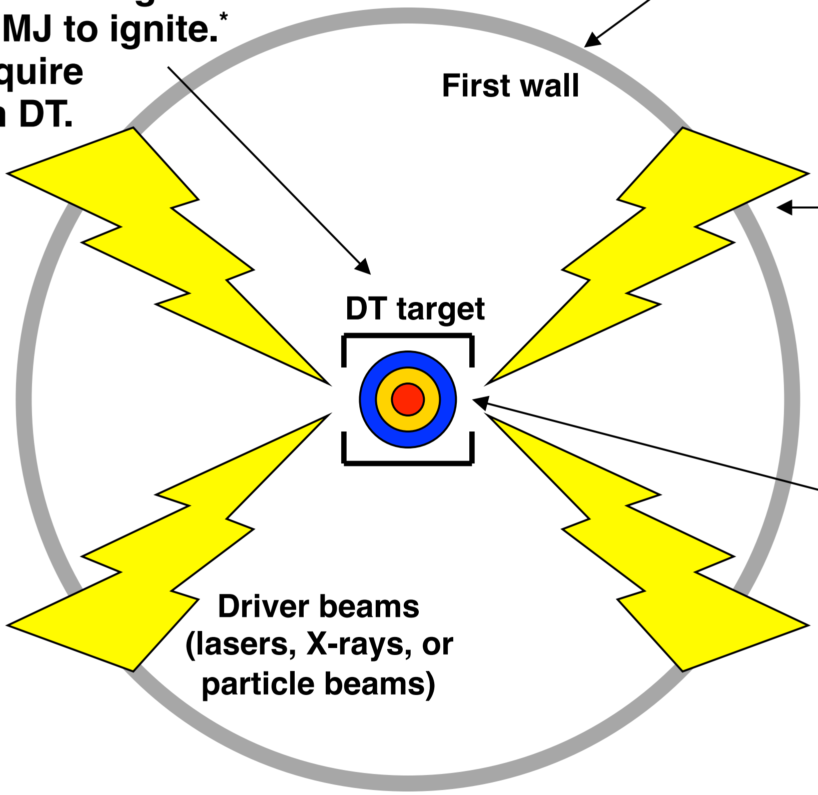
Inertial Confinement of Fusion Plasma

- Density ~ stellar core & 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.

Major problems:

(1) Halite-Centurian tests in Nevada apparently showed that DT targets might require up to 20 MJ to ignite.* DD and D^{3}He would require even more energy than DT.

(2) Cost: National Ignition Facility (NIF) is >$4B and is still not a full-fledged reactor (0.6 MJ driver energy).



(3) First wall must withstand $\sim 10^{10}$ higher peak output power than in continuous magnetic fusion reactor.

(4) Driver beam and target injection ports must be open several times per second yet shielded from damage by several large blasts per second.

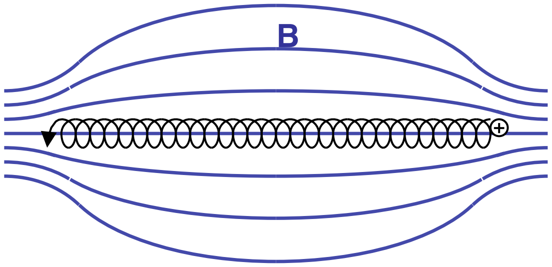
(5) Lithium breeder material in walls must be converted into precisely fabricated DT targets and accurately positioned in chamber with throughput of several per second.

---

* C. E. Paine, M. McKinzie, and T. B. Cochran, *When Peer Review Fails* Natural Resources Defense Council, www.nrdc.org/nuclear/nif2 (2000)

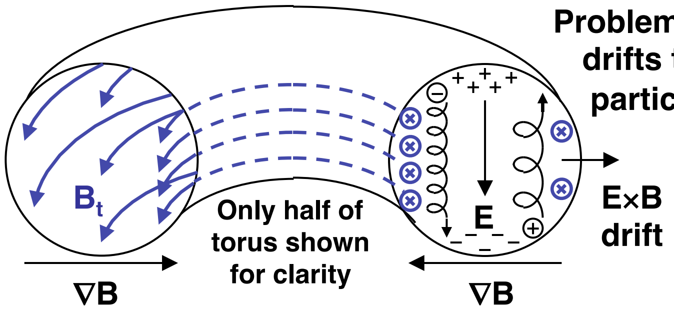
Magnetic Confinement of Fusion Plasma

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



Problem 1: Large particle losses at ends, even with magnetic mirrors, electrostatic plugs, etc.

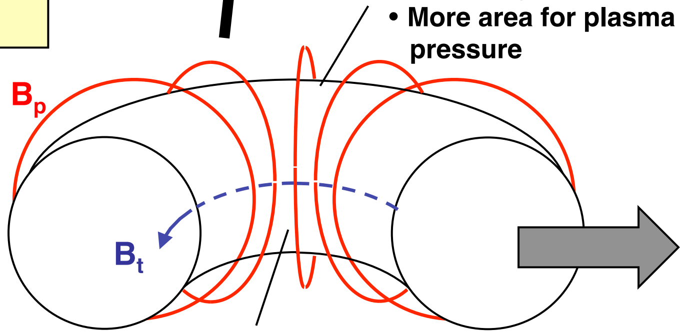
Solution 1: Eliminate the ends by bending lines into a closed toroidal field B_t



Only half of torus shown for clarity

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

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



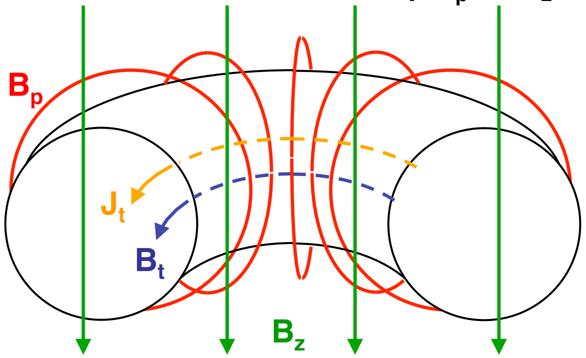
Outer wall of torus:
- Less magnetic pressure
- More area for plasma pressure

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

Problem 3: Net outward force on plasma

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



Goals (somewhat conflicting):

Maximize β ≡ plasma pressure / magnetic pressure

Minimize B inside plasma to avoid cyclotron radiation losses

Maximize fusion power density to minimize hardware cost

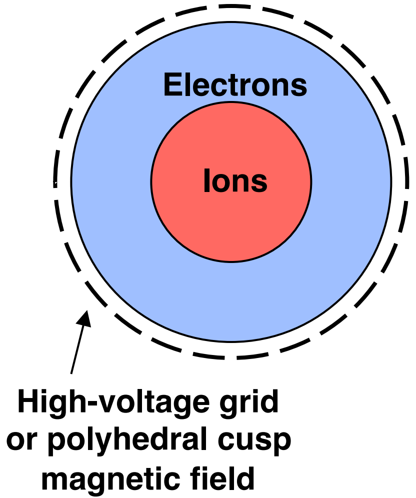
Inner hardware subject to radiation damage is inexpensive and easily accessible

Confine fuel ions and electrons but let charged products escape

Provide for lithium-6 blanket if necessary

Other Confinement of Fusion Plasmas (1)

Electrostatic

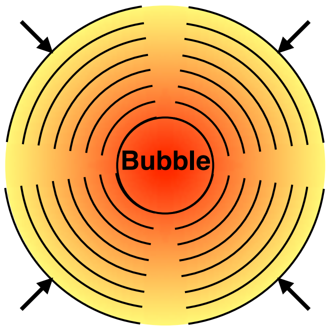


- Electron potential well confines ions but ion upscattering losses are prohibitive
- Grid or cusp field confines electrons but electron losses are prohibitive

T.H. Rider, *Phys. Plasmas* 2, 1853 (1995)

Acoustic (Sonoluminescence)

Acoustic waves in deuterated acetone

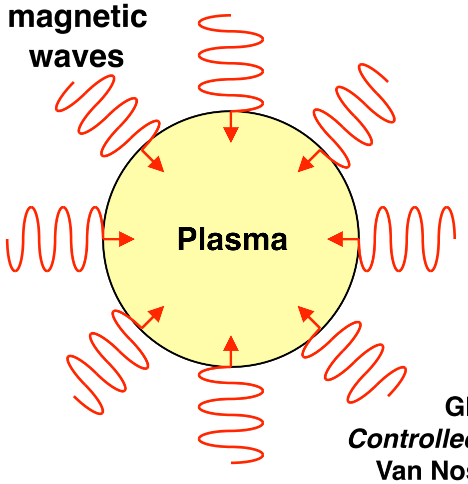


- Acoustic waves in the acetone compress bubbles to fusion conditions (?)
- Thermal conduction losses from heated region to surrounding liquid are prohibitive

R.P. Taleyarkhan *et al., Phys. Rev. E* 69, 036109 (2004)

D.J. Flannigan & K.S. Suslick, *Nature* 434, 52 & 33 (2005)

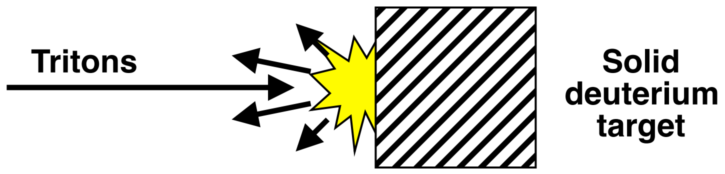
Electromagnetic



- Electromagnetic wave pressure confines plasma
- Power input is prohibitive

Glasstone & Lovberg, *Controlled Thermonuclear Reactions*, Van Nostrand (1960), pp. 437-445

Beam + Solid Target

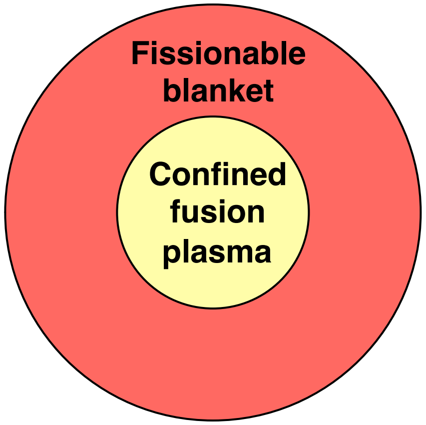


- Electrons in the target absorb far too much of the beam energy for breakeven

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

Other Confinement of Fusion Plasmas (2)

Fusion-Fission Hybrid

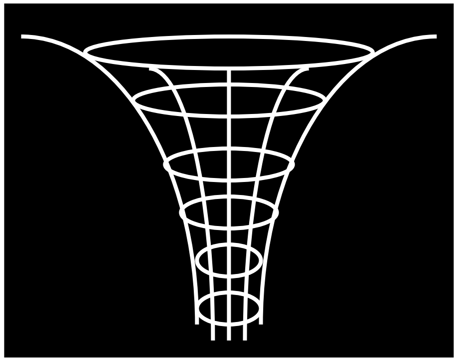


Has disadvantages of both fusion & fission:

- Fusion plasma requires expensive and complicated confinement system
- Fission blanket creates radioactive fission products and actinide waste

Small Black Hole

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

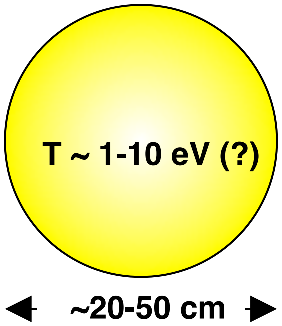


- No signs of natural small black holes in our solar system
- Creating a black hole via implosion is orders of magnitude more challenging than even ICF

L.L. Wood *et al., Annals NY Acad. Sci.* 251, 623 (1975)

Ball Lightning

Observed lifetime > 2-5 sec



- What is the confinement mechanism, especially in view of the virial theorem?
- Can this be applied to T>10 keV fusion plasmas?

Mark Stenhoff, *Ball Lightning*, Kluwer/Plenum (1999)
K.H. Tsui, *Phys. Plasmas* 10, 4112 (2003)

- 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}~300°K, T_{max}~500°K
(before something melts)

- Conventional methods add moving parts and fluids
- Thermoelectric conversion
- Thermoacoustic conversion

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

Trav. wave direct converters?[2]

Other methods?

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[1] Rosenbluth & Hinton, *Plasma Physics & Controlled Fusion* 36, 1255 (1994)

[2] Momota *et al.*, *Trans. Fus. Tech.* 27, 551 (1995)

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, *Nucl. Instr.* A522, 558 (2004)
Slutz, *Phys. Plasmas* 10, 2983 (2003)

β^- and β^+

- Direct electric converters (generally most efficient when tuned to particular β energy, but nuclear-emitted β and electrons escaping from plasmas tend to have a range of energies)
- Let positrons annihilate and convert 511-keV photons

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.*, UCRL-93988 (1986)
& *Nucl. Instr. Methods* A271, 188 (1988)

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.* UCID-16229 & 16309 (1973)

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**

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, Ph.D. thesis, MIT (1995)

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)?

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.

Fusion catalyzed by massive negative particles

- 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?
- Are there any massive negative particles that are more suitable than muons for catalysis?
- Can the effective electron mass or charge be increased in useful ways?

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?

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?

Plasma properties

- Are there realistic ways to recirculate power and maintain ions in a monoenergetic or anisotropic state, or two ion species at different temperatures (e.g. hot ^{3}He and cold D or hot p^+ and cold ^{11}B?
- Are there practical ways to reduce ion-electron energy transfer or recirculate power from the electrons back to the ions?
- Are there ways to reduce/convert radiation power losses, especially bremsstrahlung?

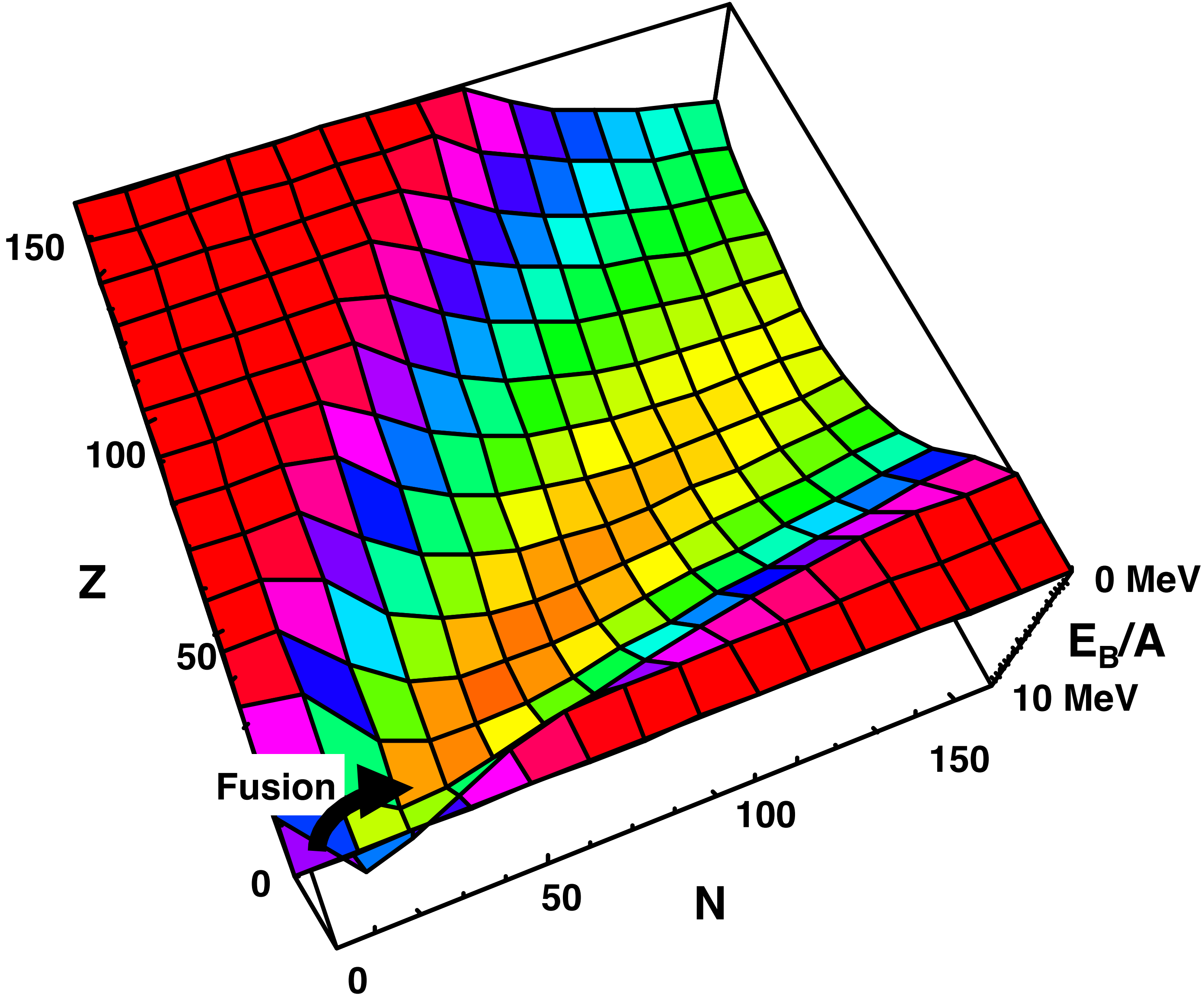
Confinement of particles and energy

- 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?
- Are there any other confinement approaches worthy of investigation?

Direct conversion

- What are the most efficient/compact thermal-to-electric converters?
- What are the best converters for light nuclei—traveling wave converters, 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 feasible and efficient are the neutron energy conversion methods of Perkins *et al.*?
- How feasible and efficient are the X-ray and γ-ray energy conversion methods of Wood *et al.*?

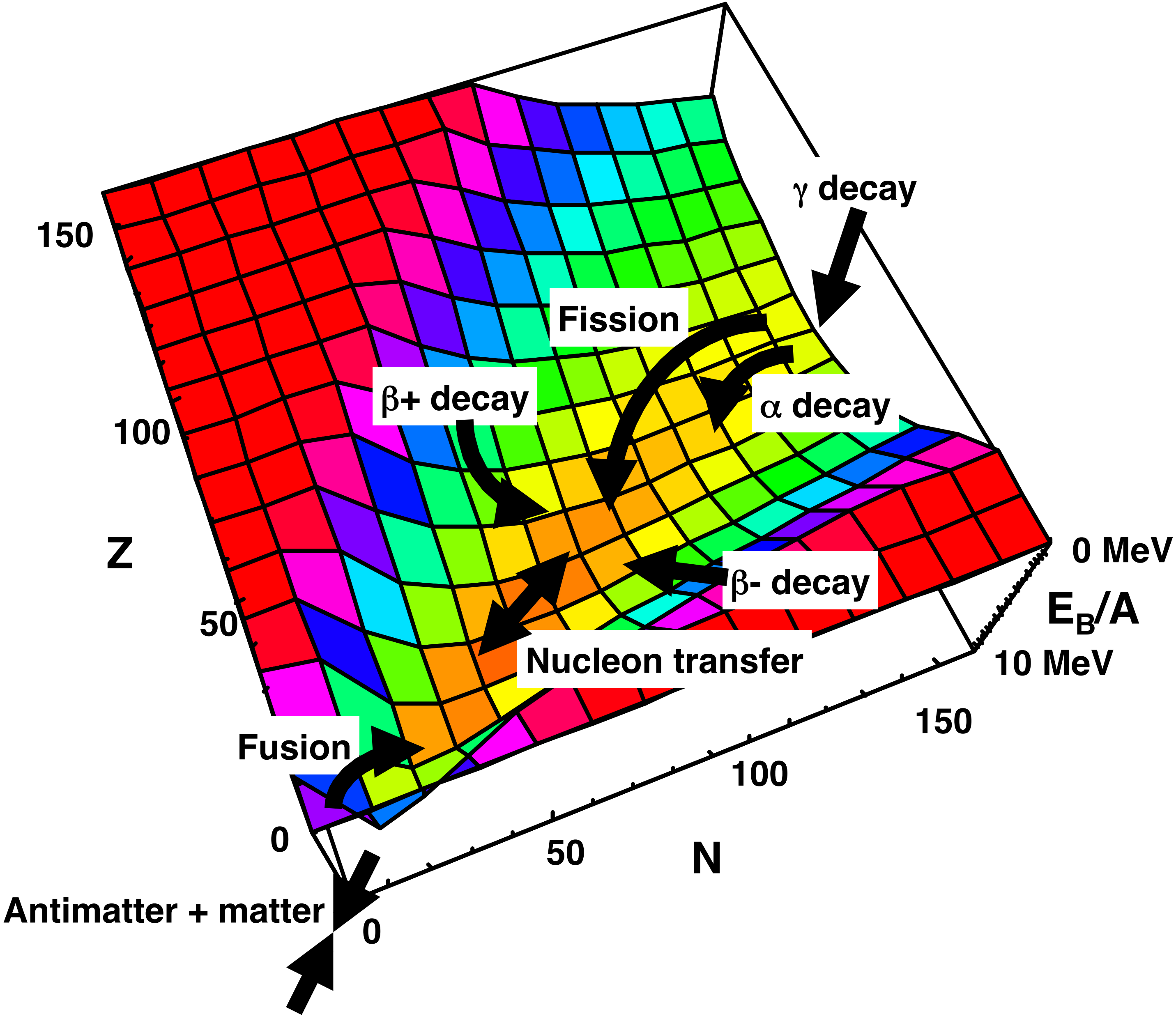
Binding Energy per Nucleon And Methods of Tapping It



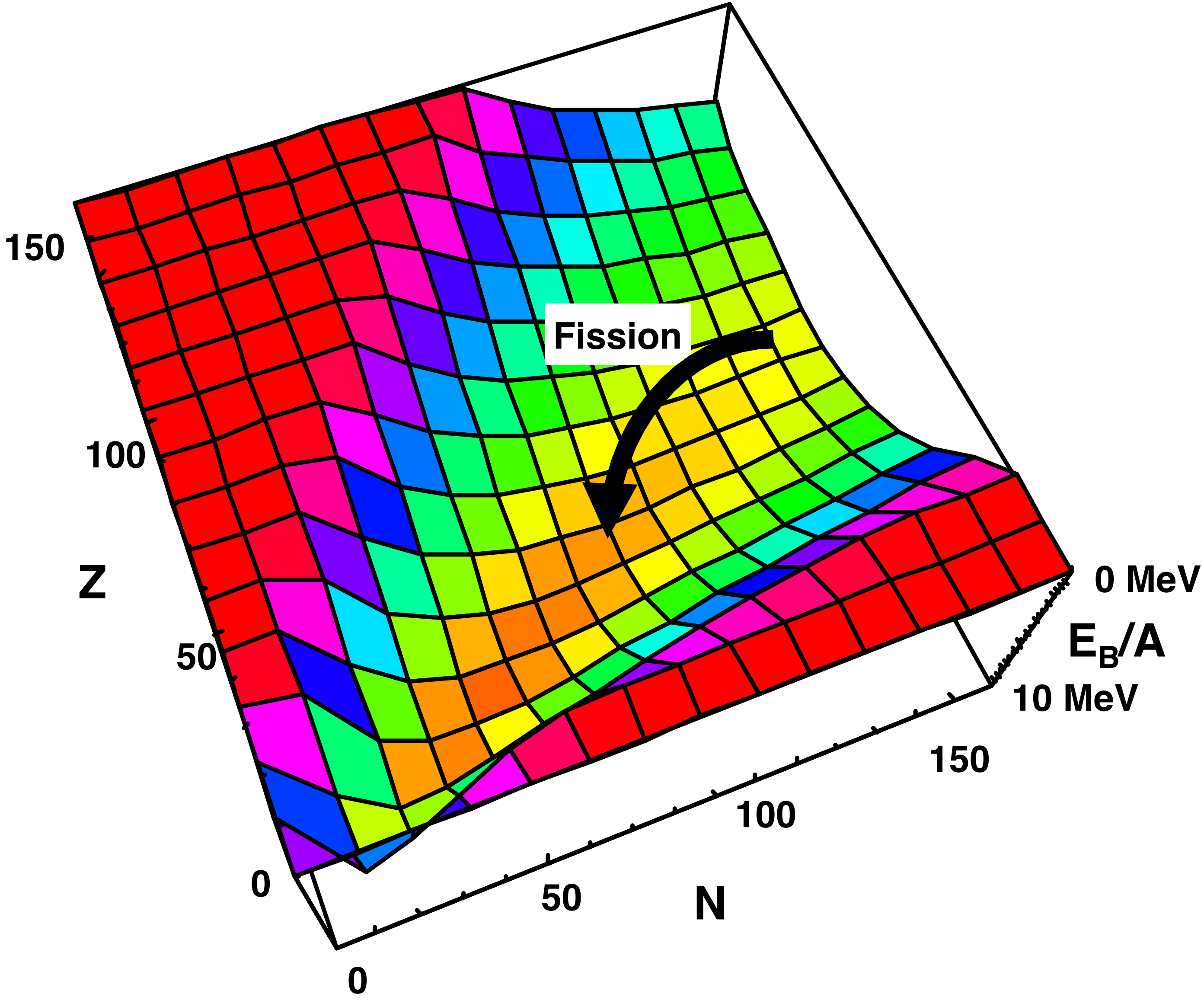
Bonus Slides:

What About Non-Fusion Approaches to Nuclear Energy?

Binding Energy per Nucleon And Methods of Tapping It



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:

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

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

\+ shell corrections

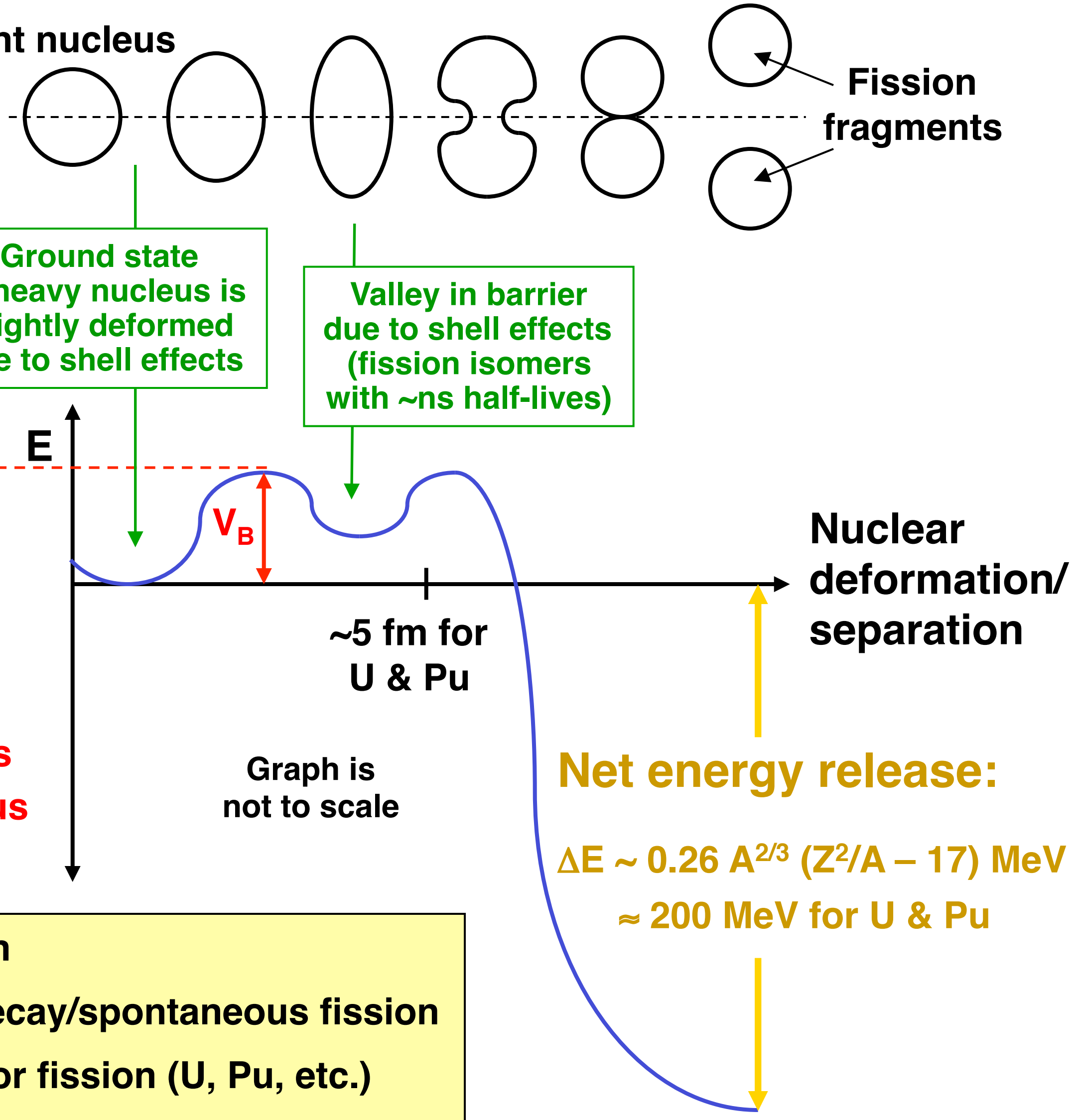
~ 5.6 MeV for even U/Pu isotopes

~ 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



Parent nucleus

Fission fragments

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)

Nuclear deformation/ separation

~5 fm for U & Pu

Graph is not to scale

Net energy release:

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

$\approx$ 200 MeV for U & Pu

- 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.)

Fission Fuels and Sources

Energy Production

Only 3 natural actinide resources:

^{235}U

- Directly useful as fuel
- Naturally mixed with ^{238}U
- >2×10^{8} kg readily accessible to mining
  → >2×10^{5} GWe-years (1/3 thermal effic.)
  → >30 years of present global energy consumption rate

^{238}U

- Transmute to ^{239}Pu fuel in breeder reactor ($n + {}^{238}\mathrm{U} \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$)
- >3×10^{10} kg readily accessible to mining
  → >2×10^{7} GWe-years
  → >5000 years of global consumption

^{232}Th

- Transmute to ^{233}U fuel in breeder reactor ($n + {}^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{Th} \xrightarrow{\beta} {}^{233}\mathrm{Pa} \xrightarrow{\beta} {}^{233}\mathrm{U}$)
- >8×10^{9} kg readily accessible to mining
  → >6×10^{6} GWe-years
  → >1000 years of global consumption

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 $^{241}\mathrm{Am}(n,\gamma)^{242m}\mathrm{Am}$

^{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

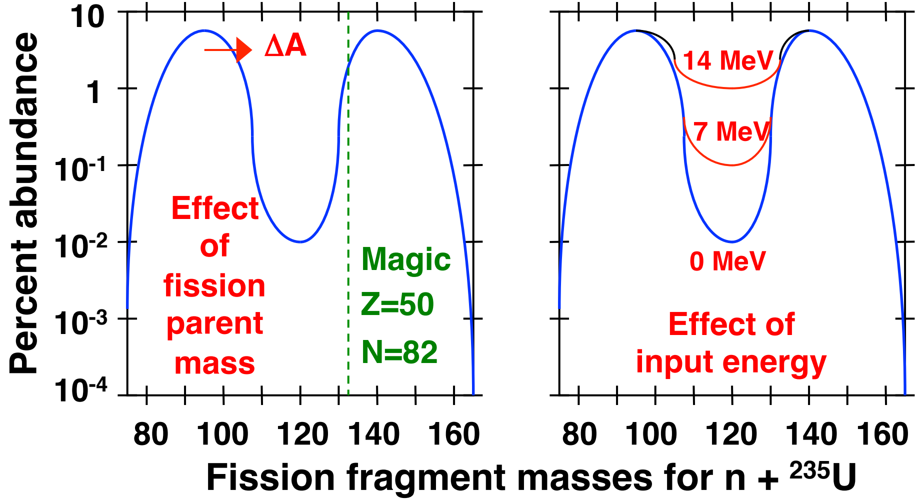
H.L. Anderson, *A Physicist's Desk Reference*, AIP (1989) p. 190.

J. Anno *et al.*, Actinides Critical Masses and the Paxton Woodcock Rule, *Proc. ICNC* (2003) 71.

Fission Waste Production

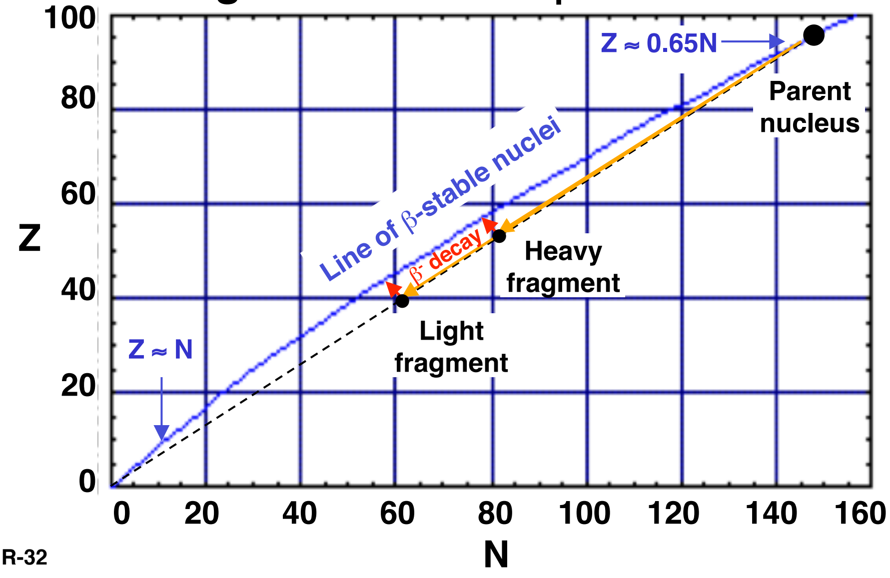
Fission fragments

Asymmetric & wide range of fragments

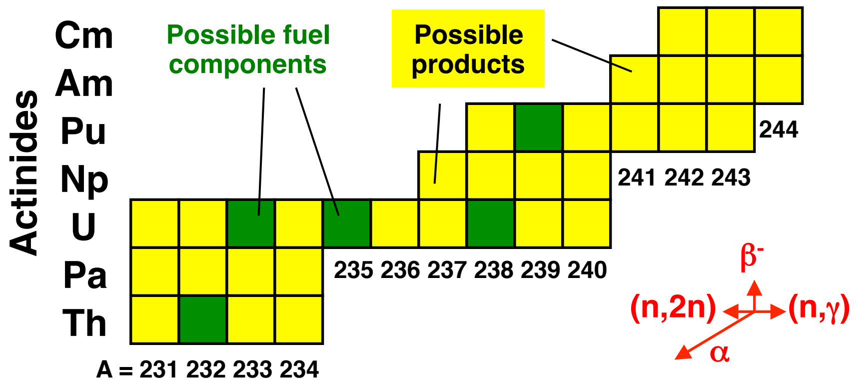


Fission fragment masses for n + ^{235}U

Fragments must be β^- emitters



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

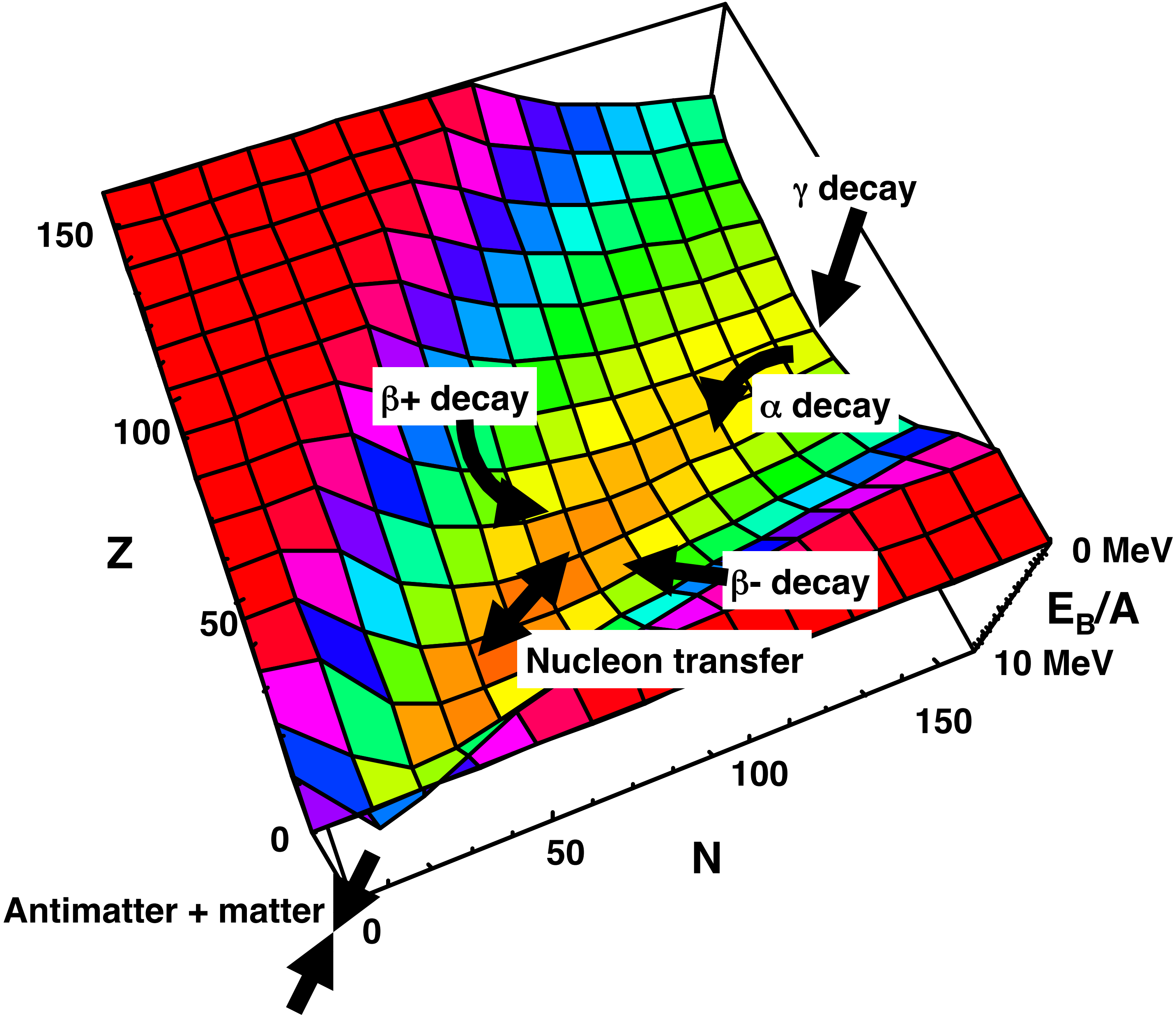
Other neutron activation

<u>Low-activation materials</u>

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.

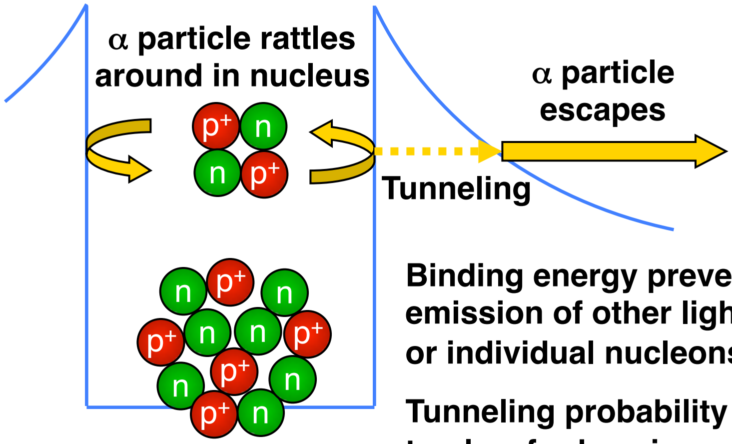
- Some tritium is produced by D_2O, ^{10}B, etc.
- Still room for improvement in low-cost, high-temperature alloys that minimize activation or embrittlement by neutrons

Binding Energy per Nucleon And Methods of Tapping It



Alpha Emission

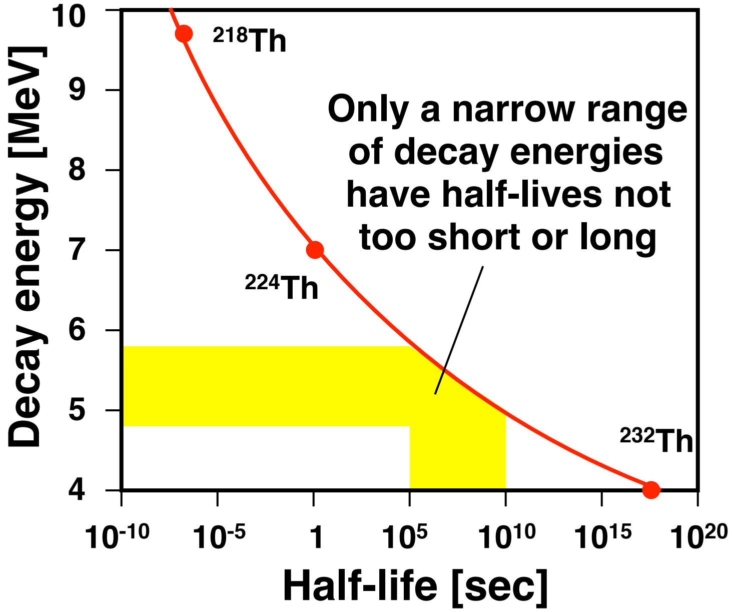
Decay mechanism



Binding energy prevents emission of other light nuclei or individual nucleons

Tunneling probability is too low for heavier nuclei

Alpha decay half-life $\tau_{1/2}$



Only a narrow range of decay energies have half-lives not too short or long

Some α emitters of interest

Nucleus	Energy	Half-life	Initial power
^{210}Po	5.3 MeV	138 days	141 W/g
^{242}Cm	6.1 MeV	163 days	120 W/g
^{244}Cm	5.8 MeV	18 years	2.8 W/g
^{238}Pu	5.5 MeV	88 years	0.56 W/g
^{241}Am	5.5 MeV	433 years	0.11 W/g

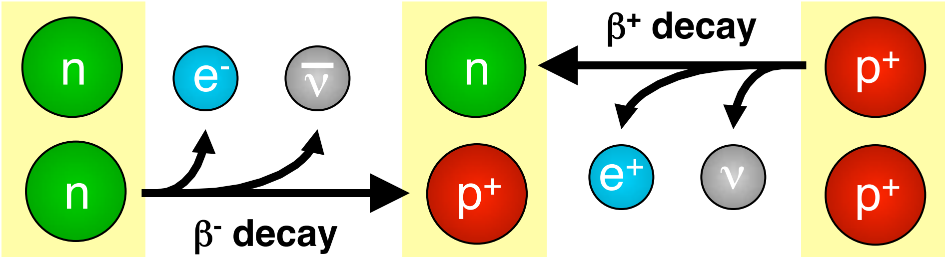
Nuclides and Isotopes (14th ed., GE, 1989)

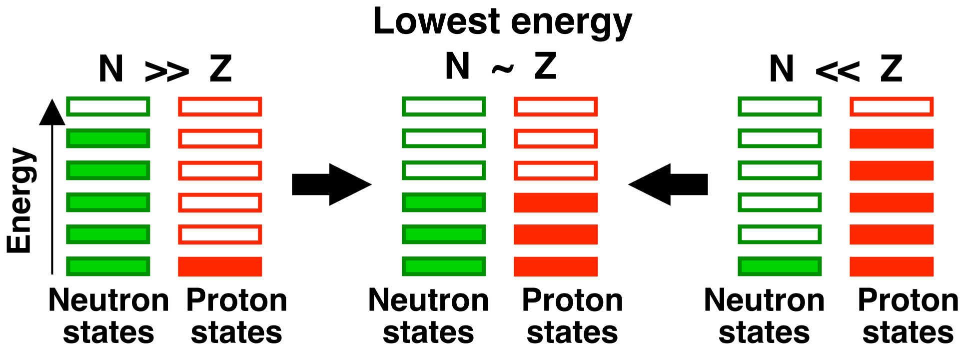
$$\frac{1}{\tau_{1/2}} \propto \left(\begin{array}{c}\text{Probability}\\ \text{that } \alpha \text{ forms}\\ \text{in nucleus}\end{array}\right)\left(\begin{array}{c}\text{Frequency with}\\ \text{which } \alpha \text{ hits}\\ \text{potential barrier}\end{array}\right)\left(\begin{array}{c}\text{Probability}\\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

- Is there a way to influence any of these factors to trigger decay on demand? (Doubtful without ~MeV input energy)
- Can α particle energy be efficiently converted directly to electricity? (Difficult with ~μm α range in solids)

Beta Emission

Decay mechanism





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
Nuclides and Isotopes (14th ed., GE, 1989)

Beta decay half-life $\tau_{1/2}$

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

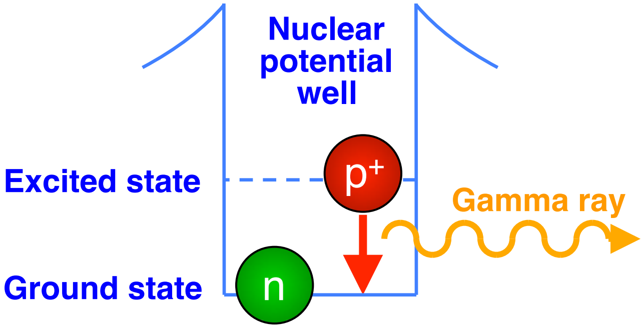
Beta emitters with
large decay energies ΔE
have short half-lives
unless the decay requires a large
emitted angular momentum L

Issues for energy storage

- Is there a way to trigger decay on demand?
- Can β particle energy be efficiently converted directly to electricity? (Difficult with ~mm β range in solids)

Gamma Emission

Decay mechanism



Gamma decay half-life $\tau_{1/2}$

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

Isomers (nuclei in excited states) with large decay energies ΔE have very short half-lives unless the decay requires a large nuclear spin change ΔJ

Some isomers of interest [1]

Nucleus	Energy	ΔJ	Half-life
^{178}Hf	2.4 MeV	16	31 years
^{198}Au	812 keV	10	2.3 days
^{182}Ta	520 keV	7	15.8 min
^{125}Te	145 keV	5	57 days
^{99}Tc	143 keV	4	6 hr
^{180}Ta	75 keV	8	$>10^{15}$ yr
^{60}Co	59 keV	3	10.5 min
^{189}Os	31 keV	3	5.8 hr
^{93}Nb	31 keV	4	16 yr

Issues for energy storage

- Are there useful isomers not in Ref. 1?
- Which isomer is best for energy storage?
- What is the best way to produce it?
- Can the decay be stimulated by γ rays despite large γ scattering? [2]
- Can other methods stimulate decay? [3-5]
- Or can one make do with the natural decay rate?
- Are internal conversion and other atomic electron processes useful?

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[1] Nuclear Wallet Cards, Brookhaven National Lab (2000)

[2] G.C. Baldwin *et al.*, *Rev. Mod. Phys*. 53, 687 (1981) and 69, 1085 (1997)

[3] B. Schwarzschild, *Physics Today* 57, 21 (2004)

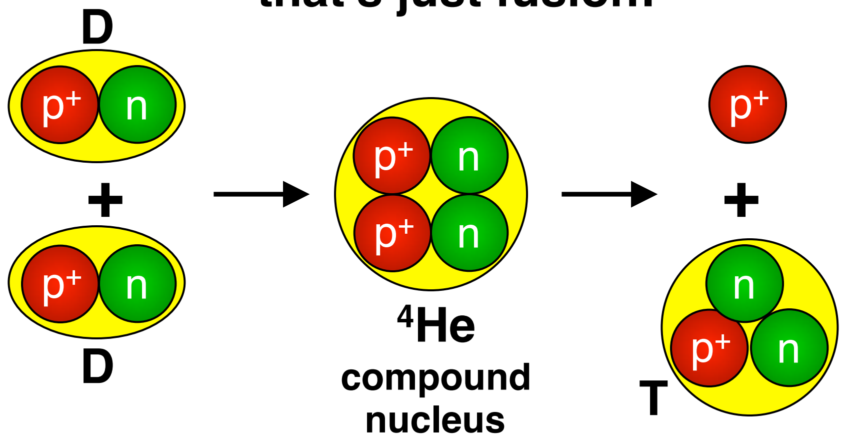
[4] A.A. Zadernovsky & J.J. Carroll, *Hyperfine Interactions* 143, 153 (2002)

[5] J.A. Becker *et al.*, Isomer Research DOE Project 2000-123 (2003)

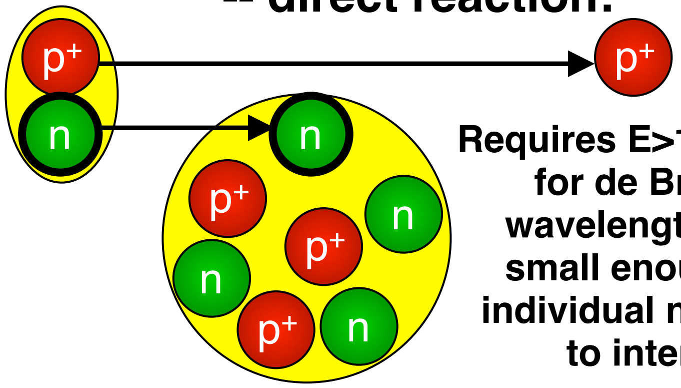
Nucleon Transfer Between Nuclei

Nuclei contact each other

Temporarily form compound nucleus -- that's just fusion:

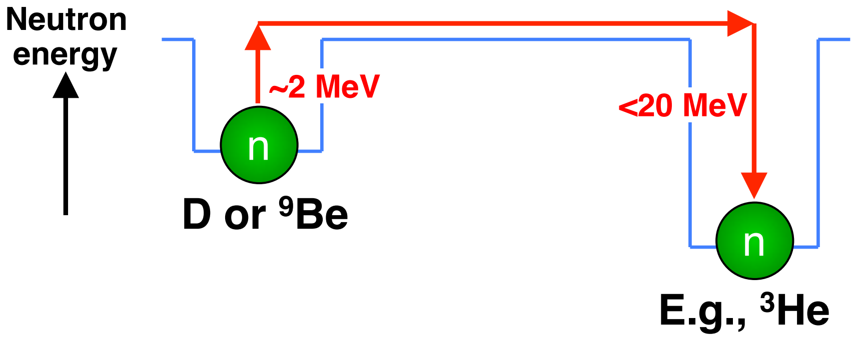


Do not form compound nucleus -- direct reaction:



Requires E>10-20 MeV for de Broglie wavelength to be small enough for individual nucleons to interact

Nuclei not in contact



Much easier to transfer neutrons than protons—no Coulomb barrier

Difficult to supply input & remove output energy without fission

Less output than fusion & fission

Proposed magical neutron transfer methods (no evidence)[1-2]:

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

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[1] J. R. Huizenga, *Cold Fusion* (Oxford, 1993)
[2] www.lenr-canr.org

Antimatter

Use

Antimatter + matter → 100% of mass is converted to energy (vs. ~1% 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

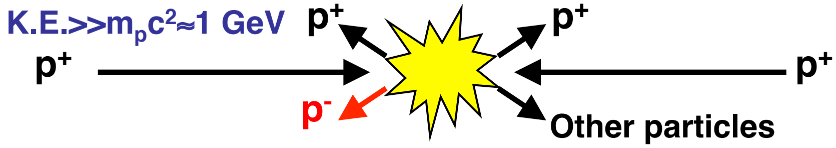
→ Need positrons and antiprotons to keep antimatter (nearly) neutral

Energy produced as pions & γ rays

Production

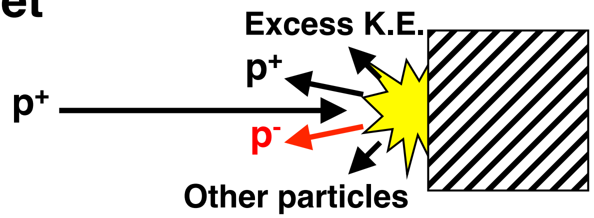
Much more difficult to make antiprotons (p^-) than positrons (e^+)

Proton (p^+) beam-beam collider:



- $< 2 \times 10^{-3}$ 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
- $< 2 \times 10^{-4}$ 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, *Journal of Propulsion and Power* 13, 435 (1997)