Is There a Better Route to Fusion?

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“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.’”

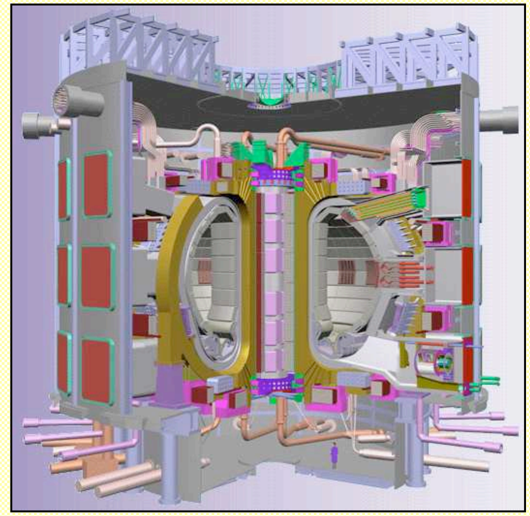
-Mark Twain, “Dr. Loeb’s Incredible Discovery” (1910)

Motivation

Three Mile Island

Current fission power approaches are not ideal

- Politically incorrect amount of radioactivity
- Conventional reactors are very expensive (>$1B each)



ITER

Current fusion power approaches are not ideal

- Also quite radioactive and more expensive than fission reactors (>$5B for ITER)
- 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?

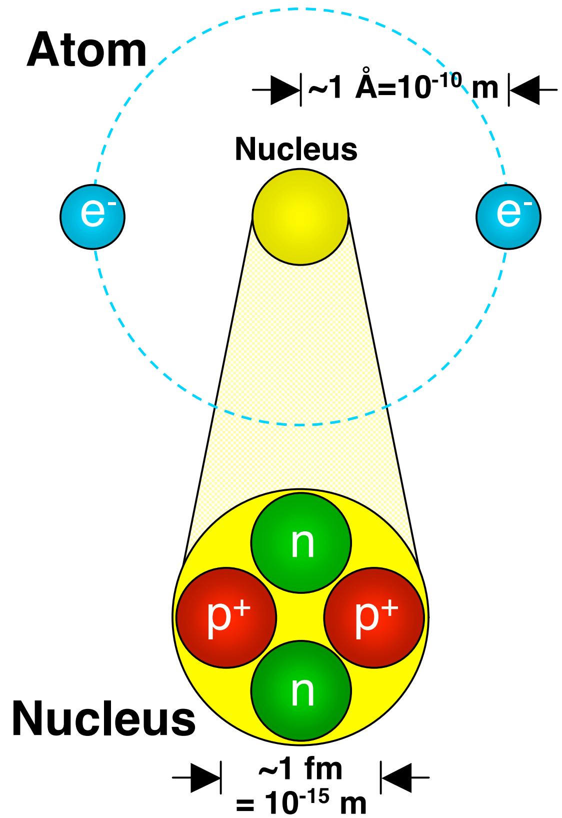
Nuclear vs. Chemical Energy

From Coulomb's law:

$$E \sim \frac{e^2}{4\pi\varepsilon_o r} = \frac{14.4 \text{ eV}}{r \;\; [\text{in Å}]}$$

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

(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)

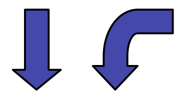
$$E_B = 16\,A \;-\; 17\,A^{2/3} \;-\; 0.7\,\frac{Z^2}{A^{1/3}} \;-\; 25\,\frac{(N-Z)^2}{A} \;+\; \left\{\begin{array}{ll} 34\,A^{-3/4} & \text{even } N, Z \\ 0 & \text{odd-even} \\ -34\,A^{-3/4} & \text{odd } N, Z \end{array}\right\} \;+\; \sim\frac{A}{20}$$

if N or Z is magic

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

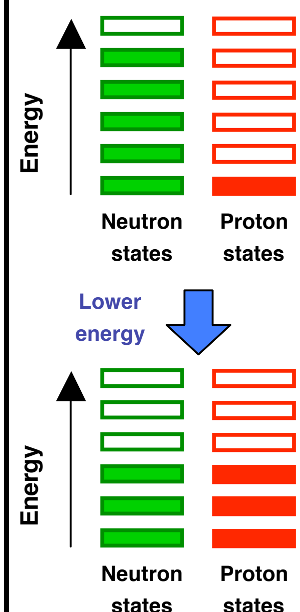
Correction: nuclei at surface have fewer neighbors for binding energy

Coulomb repulsion among protons (favors N >> Z)

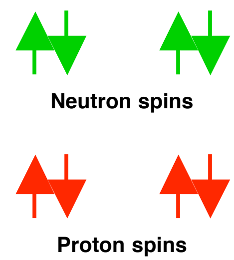


Favors N a bit larger than Z, especially for large nuclei

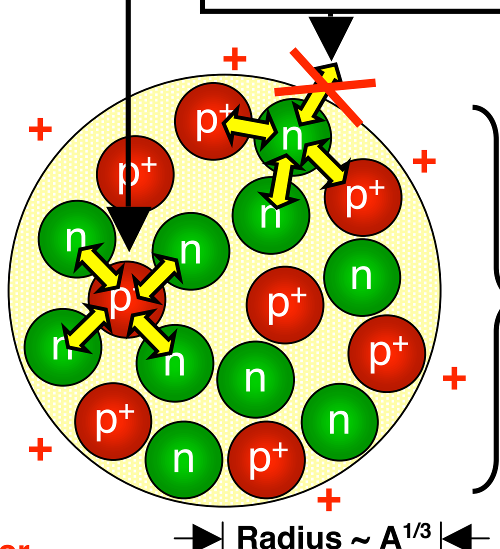
Energy cost of not filling neutron and proton states to same level (favors N ≈ Z)



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)



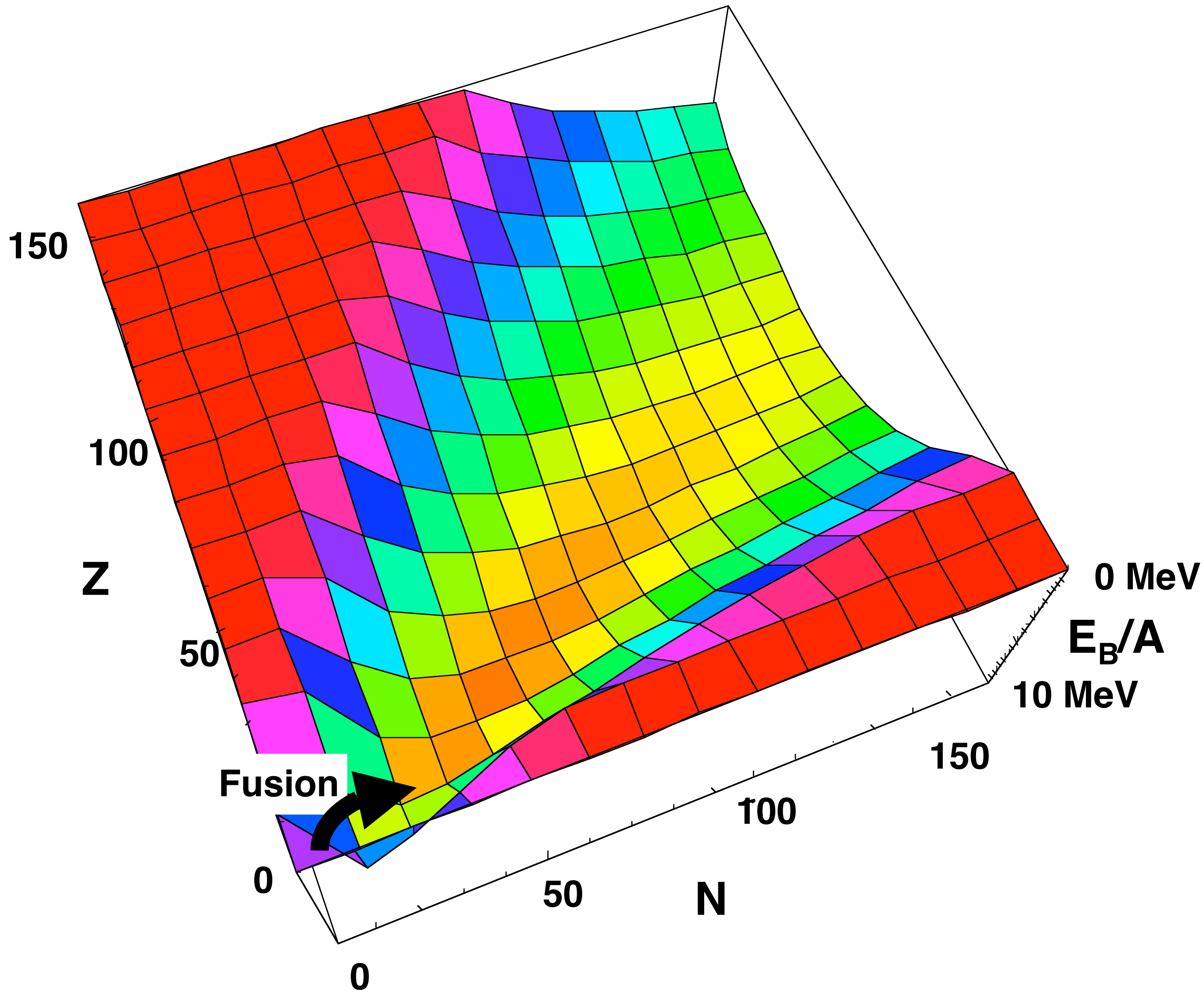
Radius ~ $A^{1/3}$

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

Volume ~ A

Valid for A ≥ 15

Binding Energy per Nucleon And Methods of Tapping It



Possible Fusion Reactions

Input nucleus 2

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

Neglect:

- Nuclei with □$_{1/2}$ < 1 min
- 3-body fusion

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 3□ 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						

$Z_1Z_2 \geq 8$

Coulomb barrier is too high

$Z_1Z_2 \geq 7$ Coulomb barrier is too high

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4/1/05

Physical Factors in Fusion Cross Section (in barns)

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

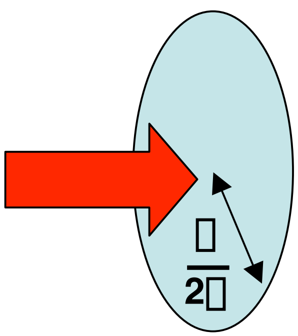
$$\sigma_{fus} = \frac{650}{A_{red} E_{CM}} \frac{(2J+1)}{(2J_1+1)(2J_2+1)} \exp\left[-31.4 Z_1 Z_2 \sqrt{\frac{A_{red}}{E_{CM}}} + 1.154 \sqrt{Z_1 Z_2 A_{red}\left(A_1^{1/3}+A_2^{1/3}\right)}\right] \frac{(\Gamma E)^2}{(E_{CM}-E_r)^2+(\Gamma E/2)^2}$$

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

Probability of tunneling through Coulomb barrier between nuclei

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

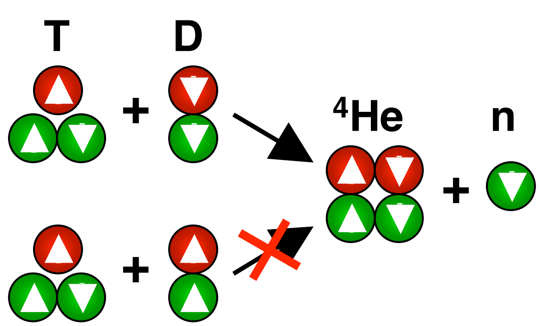
Diffraction-limited cross-sectional area $\approx \pi(\lambda/2\pi)^2$ for wavefunctions of colliding nuclei

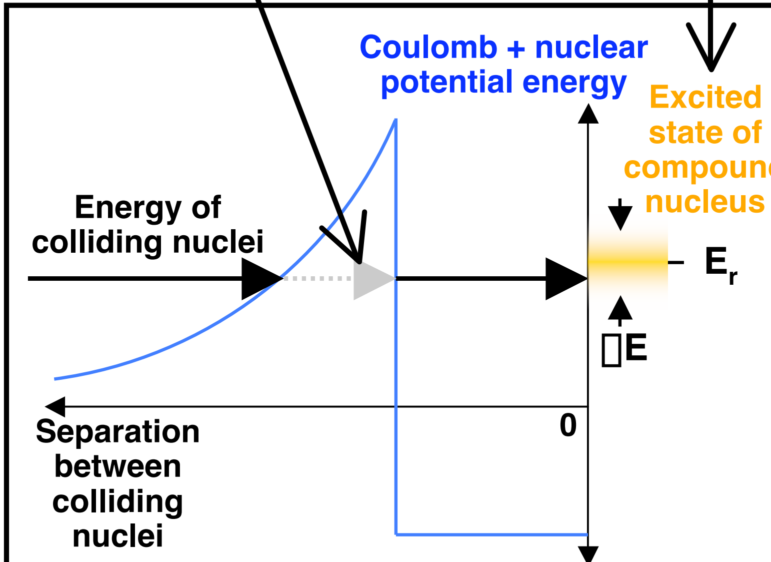


Input nuclei must have correct spins to fuse

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





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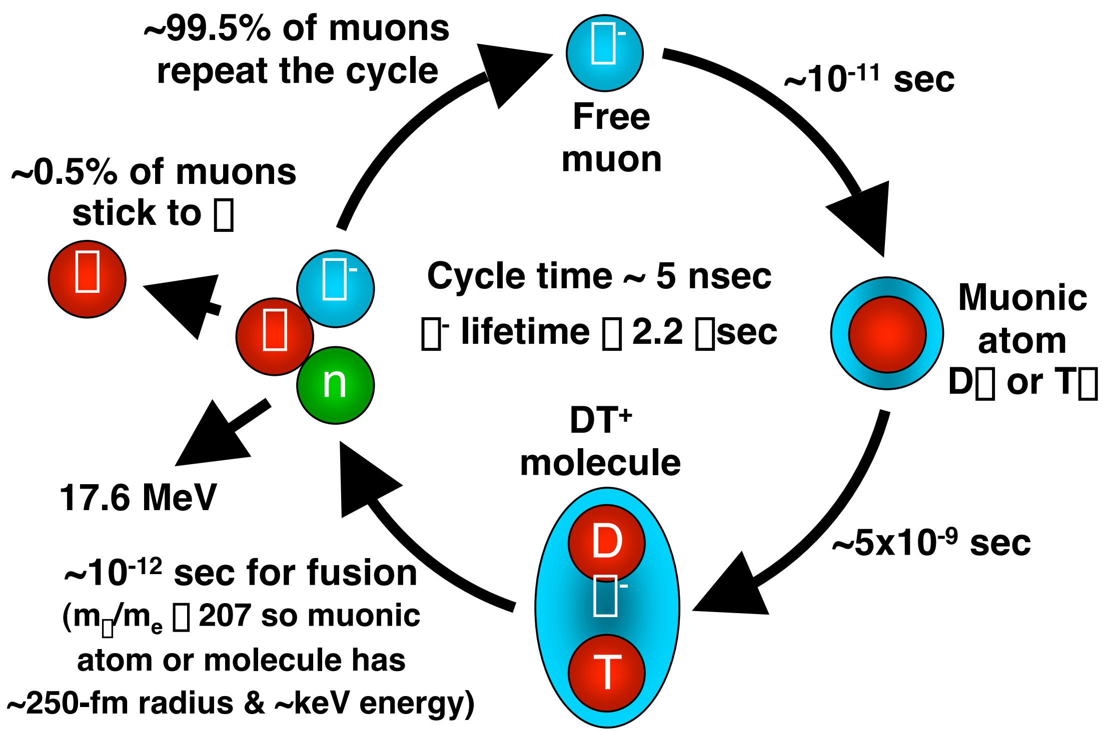
Improve Spin Polarization Factor in σ_{fus}

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

[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]



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.
$\Rightarrow$ 1 GeV useful output per μ^-

Need unsticking methods

Could then catalyze 2.2μs / 5ns
$\Rightarrow$ 440 fusions before μ^- decays

Need way to reduce cycle time [2]

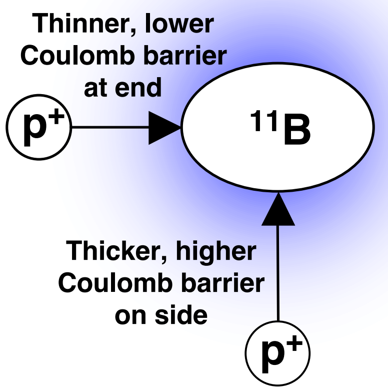
Performance is much worse for reactions other than D+T

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]

[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



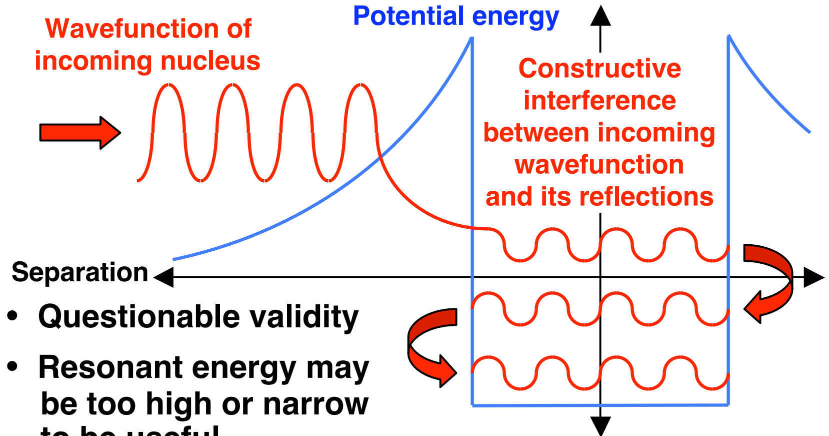
σ_{fus} for end only is ~10x larger than angle-averaged σ_{fus}

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

much faster than fusion

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

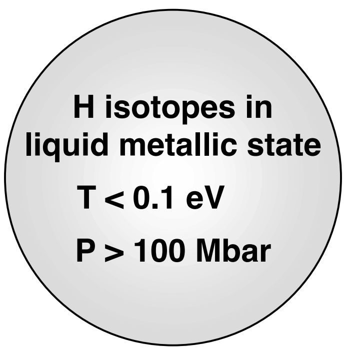
Resonant tunneling



- 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



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

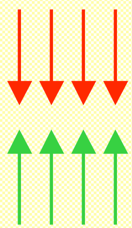
σ_{fus} is greatly increased by
- electron screening of Coulomb potential
- many-particle correlations among nuclear states

- 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

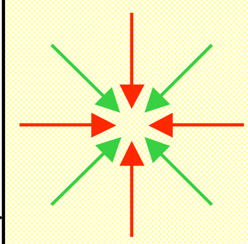


Ion species 2

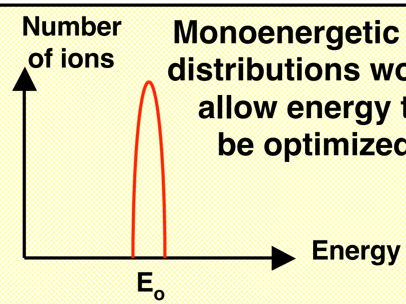
Highly anisotropic velocity distributions would allow collisions to have best CM energy

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

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

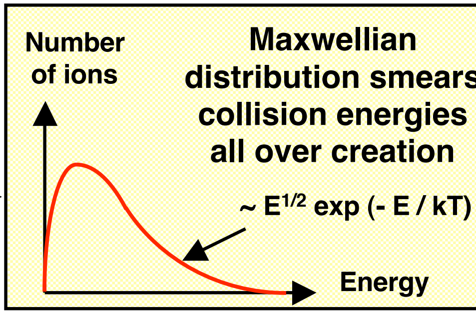


Approximately isotropic distributions collide at wide range of CM energies

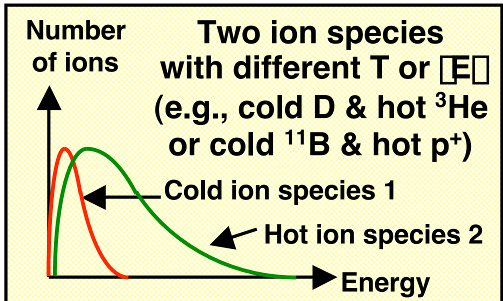


Monoenergetic ion distributions would allow energy to be optimized

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

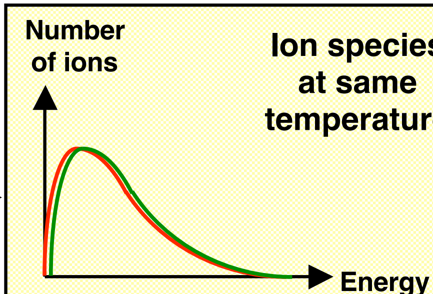


Maxwellian distribution smears collision energies all over creation



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

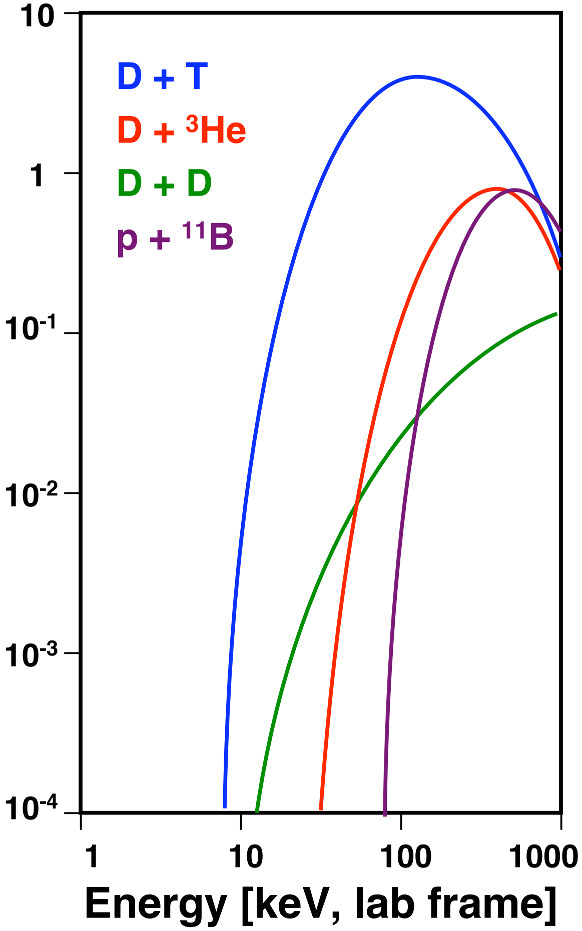


Ion species at same temperature

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

Cross Sections for Major Fusion Reactions

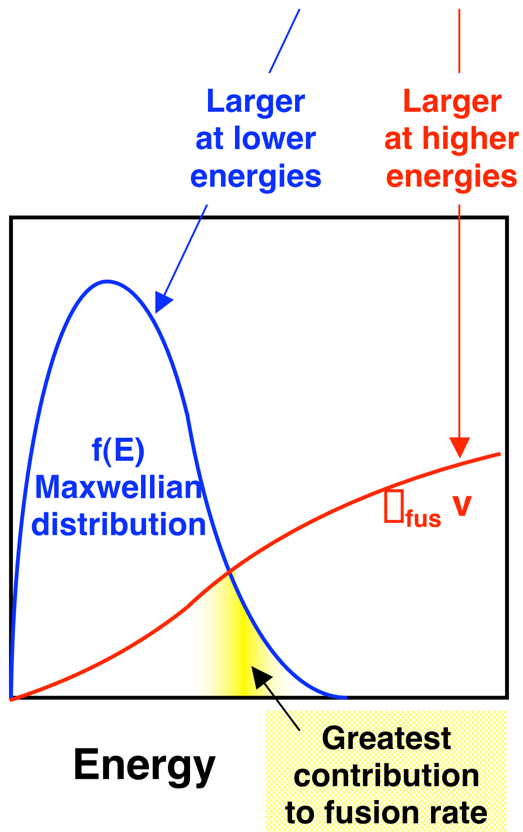
σ_{fus} [barns] for major reactions



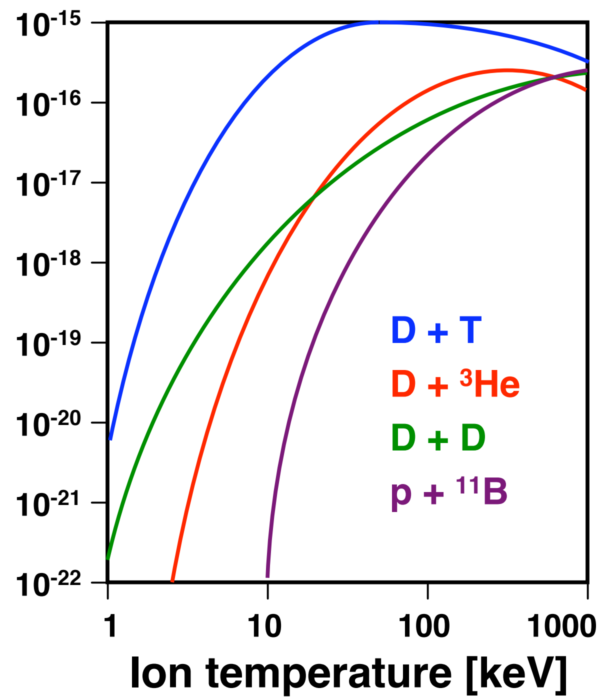
Reaction rate/volume

$= \langle\sigma_{fus}\, v\rangle n_{i1}\, n_{i2}$

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



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



Electrons

You Can't Live Without Them

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

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

$$\Rightarrow n_i < \frac{B^2/2\varepsilon_o}{m_i c^2}$$

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

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 $T_i >> T_e$:

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

~ 1 for $Z\sim 1$, $\ln\Lambda\sim 20$, $E_{fus}\sim 18$ MeV
$\langle\sigma v\rangle\sim 2\text{x}10^{-16}$ cm^3/sec,
$T_i/T_e\sim 5$, $A\sim 2$, $T_i\sim 100$ keV

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

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

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

Actually it's worse—see next slide…

Electrons Lose Energy via Bremsstrahlung Radiation

If photons are confined

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

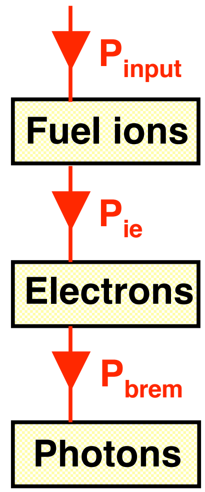
$$\frac{E_{photons}}{E_{ions}} \approx \frac{8\,\sigma_{SB}\,T^3}{3\,c\,k_B\,n_i}$$

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

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

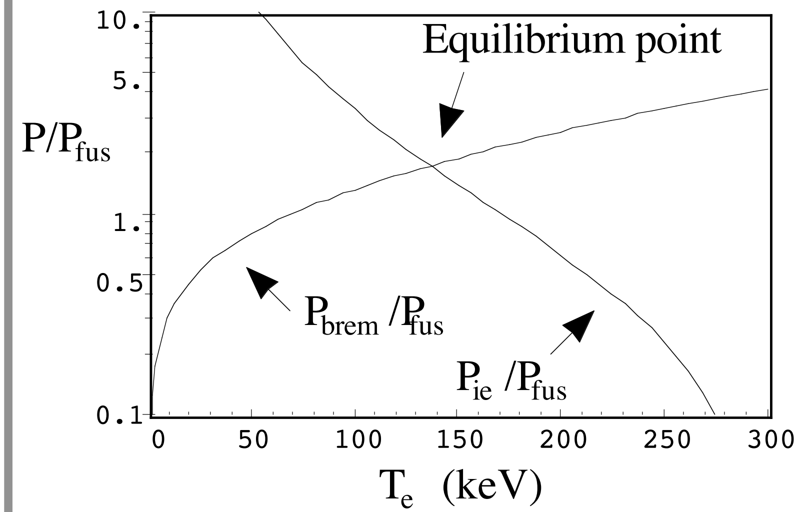
Just ~10 keV even for a stellar core ($n_i \sim 10^{26}$ cm^{-3})

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



If photons escape

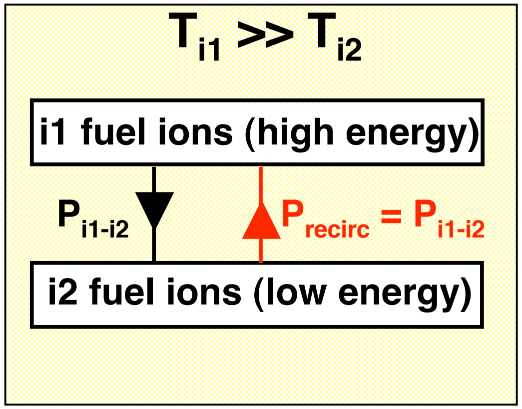
E.g.: 5:1 $p+^{11}B$ with T_i=300 keV

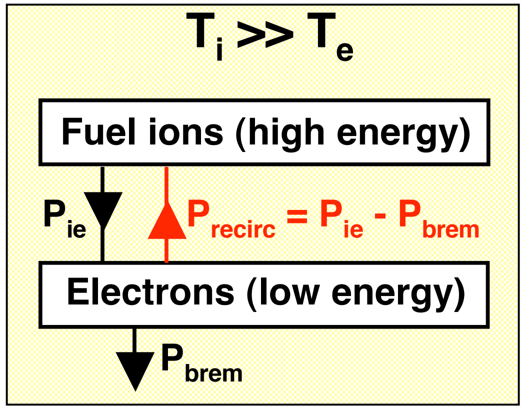


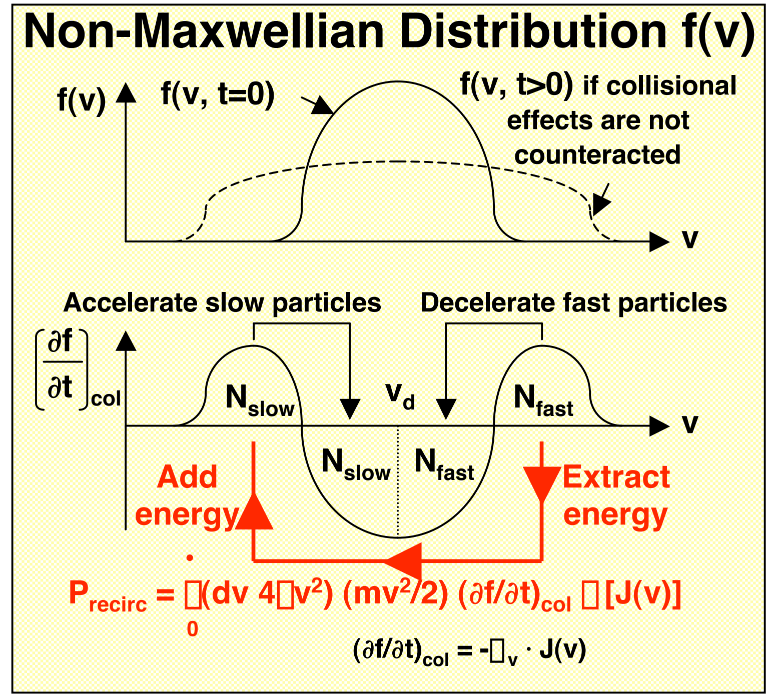
Minimum P_{brem}/P_{fus}

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	

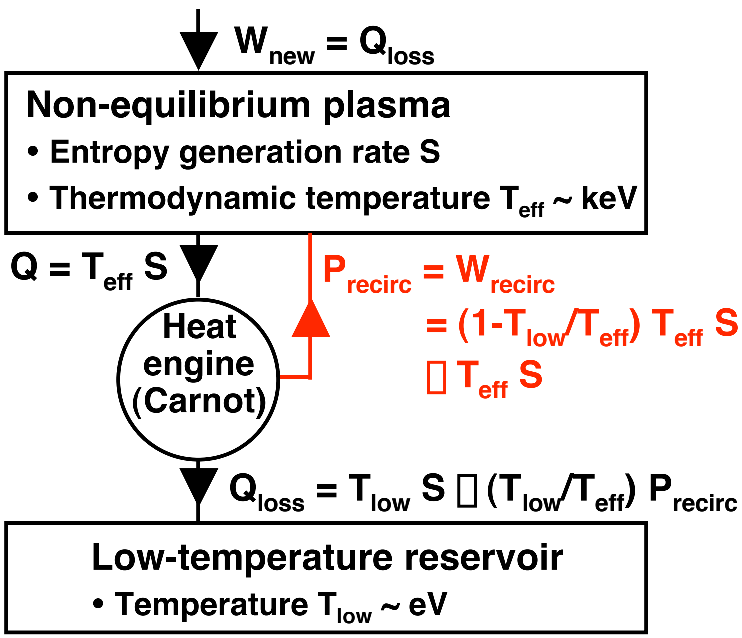
Required Power to Maintain Nonequilibrium Plasma







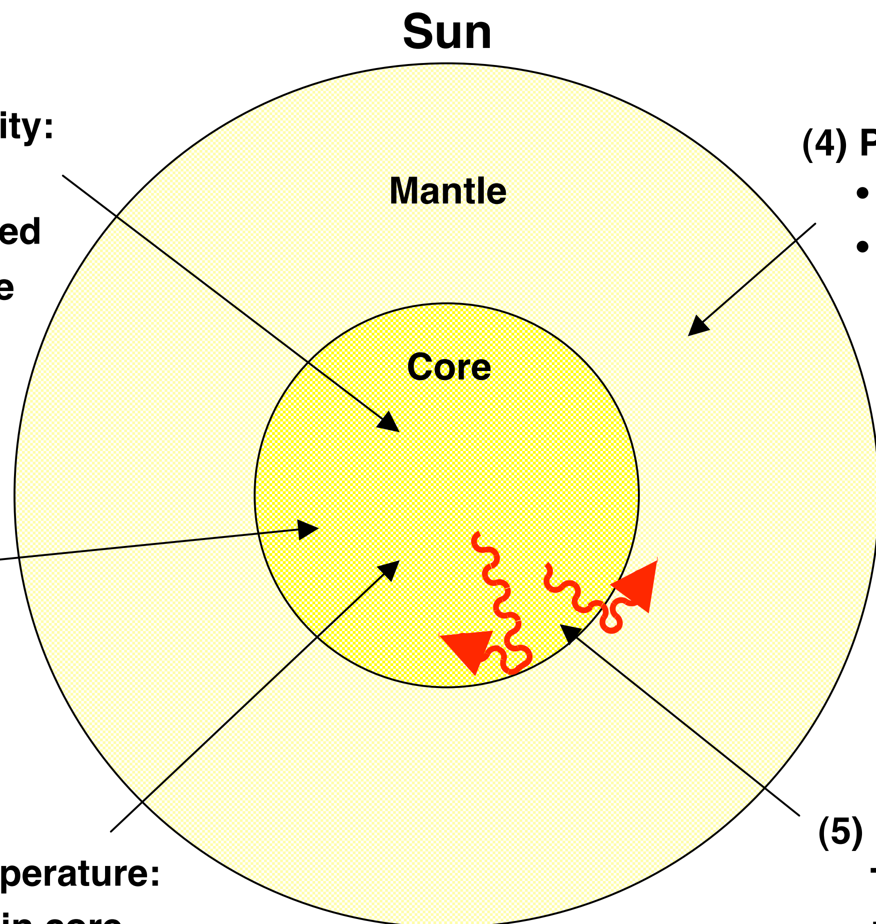
Idealized System for Recirculating Power to Maintain a Nonequilibrium Plasma



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

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

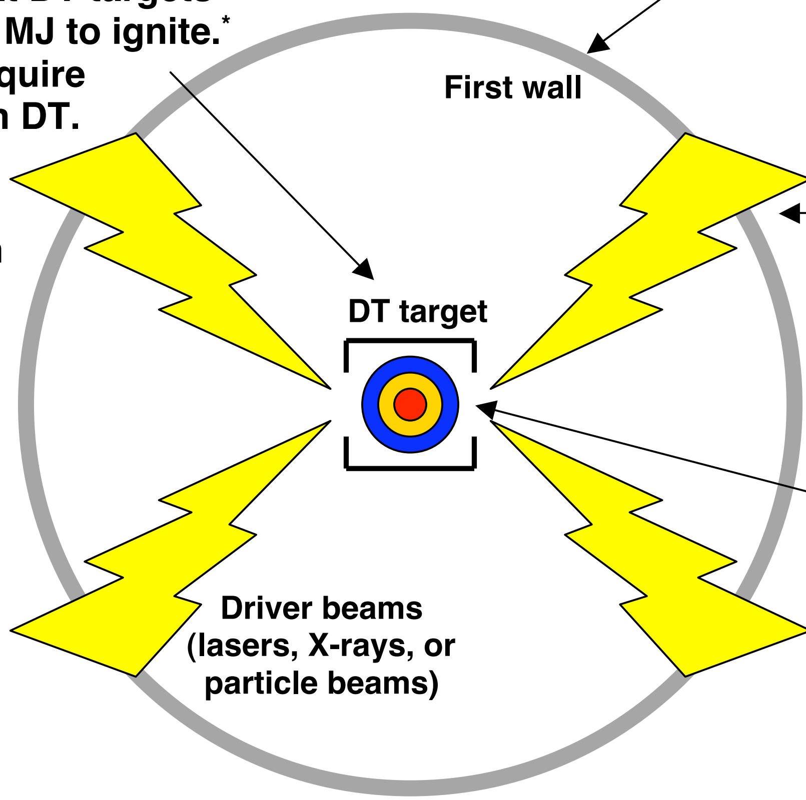
(1) Halite-Centurian tests in Nevada apparently showed that DT targets might require up to 20 MJ to ignite.* DD and D^{3}He would require even more energy than DT.

(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 ~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.



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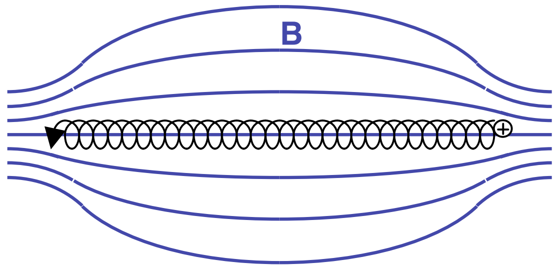
* C. E. Paine, M. McKinzie, and T. B. Cochran, *When Peer Review Fails* Natural Resources Defense Council, www.nrdc.org/nuclear/nif2 (2000)

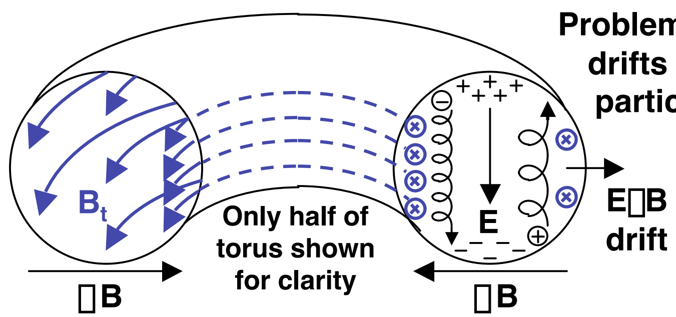
Magnetic Confinement of Fusion Plasma

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



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

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

Maximize β ≡ plasma pressure / magnetic pressure

Minimize B inside plasma to avoid cyclotron radiation losses

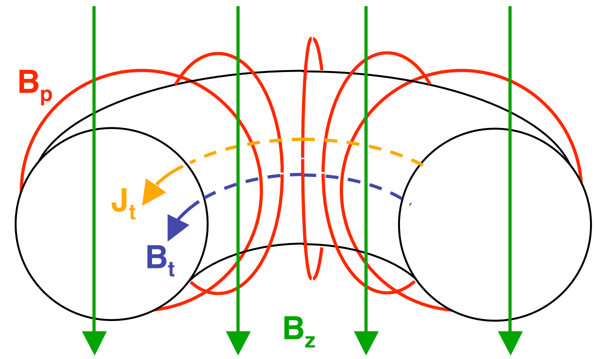
Maximize fusion power density to minimize hardware cost

Inner hardware subject to radiation damage is inexpensive and easily accessible

Confine fuel ions and electrons but let charged products escape

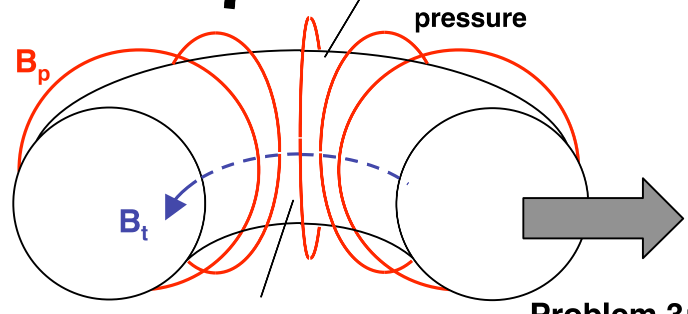
Provide for lithium-6 blanket if necessary

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



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

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

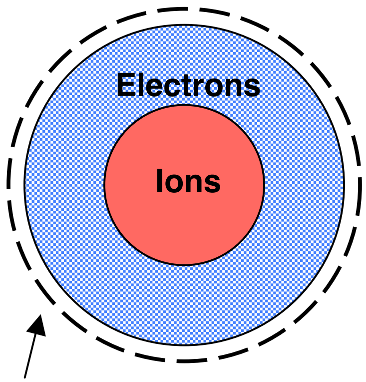


Inner wall of torus:
- More magnetic pressure
- Less area for plasma pressure

Problem 3: Net outward force on plasma

Other Confinement of Fusion Plasmas (1)

Electrostatic



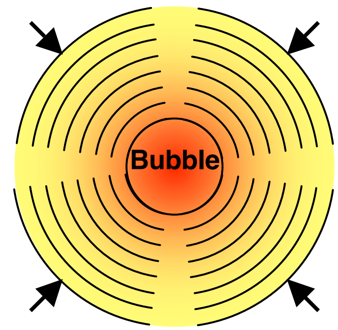
High-voltage grid or polyhedral cusp magnetic field

- 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, *Phys. Plasmas* 2, 1853 (1995)

Acoustic (Sonoluminescence)

Acoustic waves in deuterated acetone

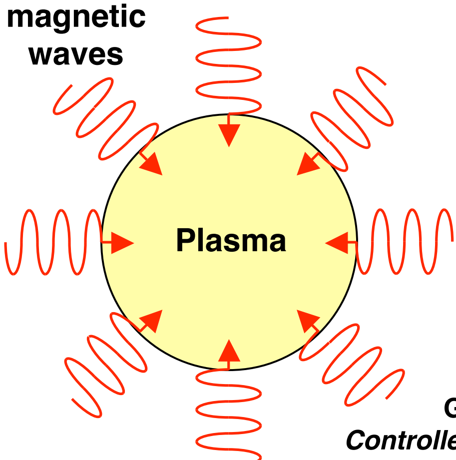


- Acoustic waves in the acetone compress bubbles to fusion conditions (?)
- Thermal conduction losses from heated region to surrounding liquid are prohibitive

R.P. Taleyarkhan *et al., Phys. Rev. E* 69, 036109 (2004)
D.J. Flannigan & K.S. Suslick, *Nature* 434, 52 & 33 (2005)

Electromagnetic

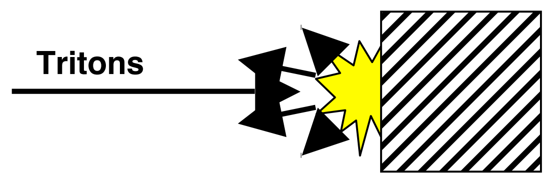
Electro-magnetic waves



- Electromagnetic wave pressure confines plasma
- Power input is prohibitive

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

Beam + Solid Target



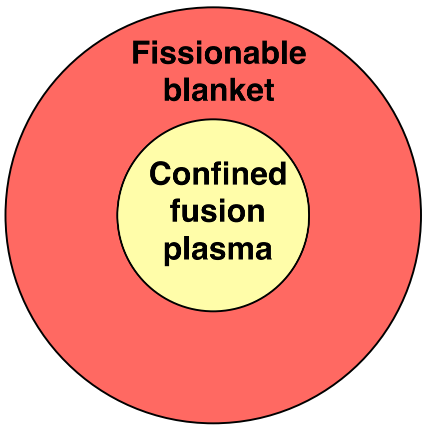
Solid deuterium target

- 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

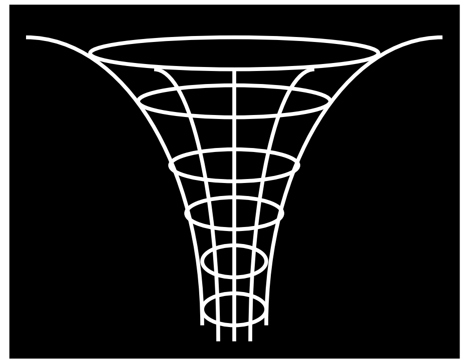


Has disadvantages of both fusion & fission:

- 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

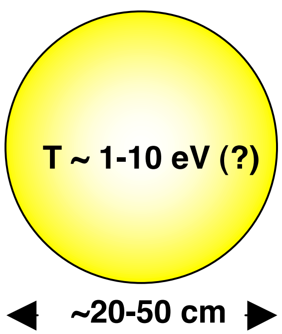


- No signs of natural small black holes in our solar system
- Creating a black hole via implosion is orders of magnitude more challenging than even ICF

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?

[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

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 cannot work

- **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

<u>Fusion products</u>

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

<u>Plasma properties</u>

- 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?

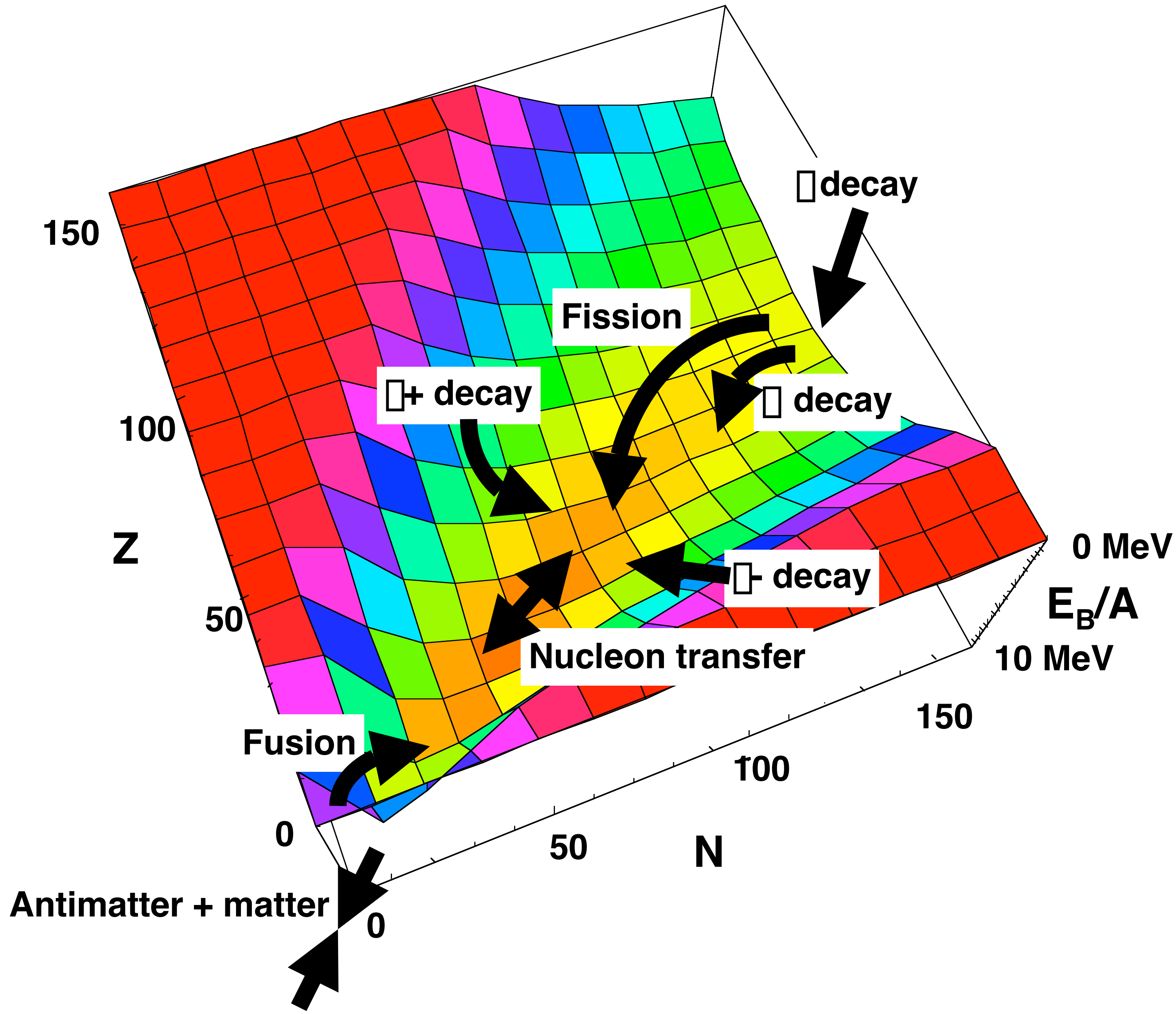
<u>Confinement of particles and energy</u>

- 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?

<u>Direct conversion</u>

- 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



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