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?

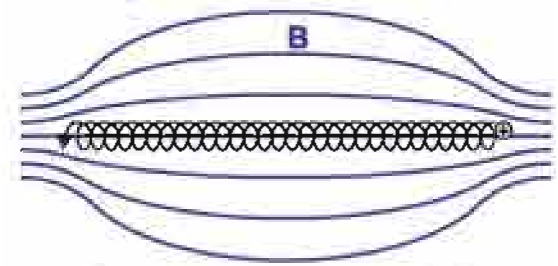
How many more decades would be required to achieve that goal?

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

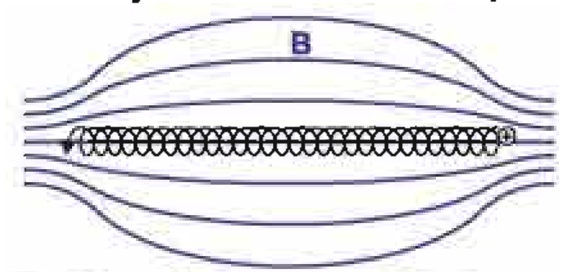
Charged particles spiraling along magnetic field lines B cannot easily cross them to escape



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

Magnetic Confinement of Fusion Plasma

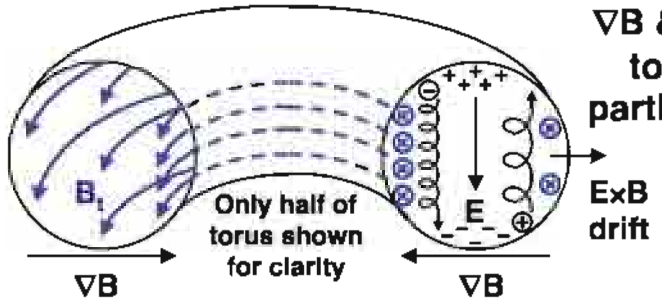
Charged particles spiraling along magnetic field lines B cannot easily cross them to escape



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 & $E \times B$ drifts together let particles escape



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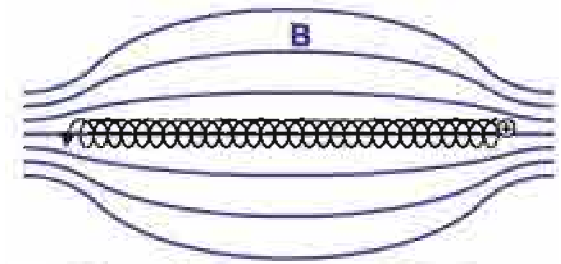

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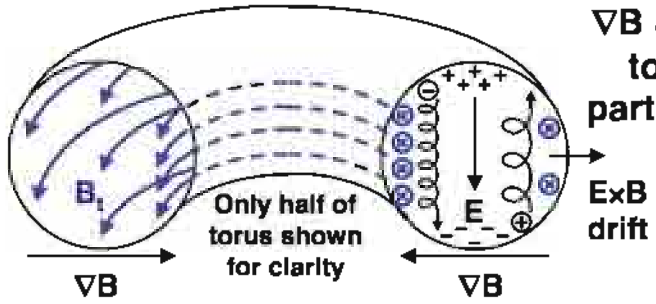
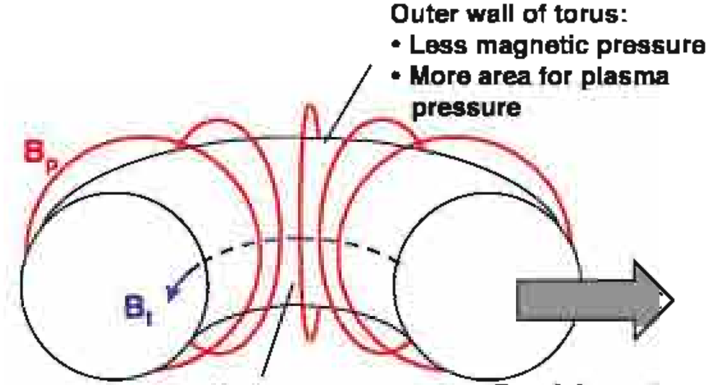


Problem 2: ∇B & E×B drifts together let particles escape

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



Problem 3: Net outward force on plasma

Magnetic Confinement of Fusion Plasma

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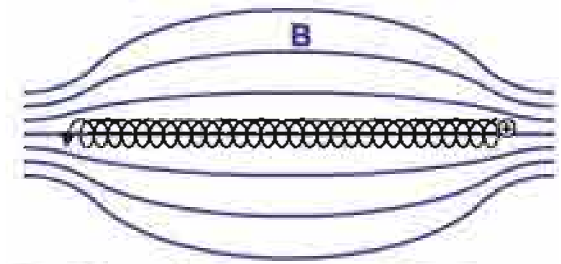

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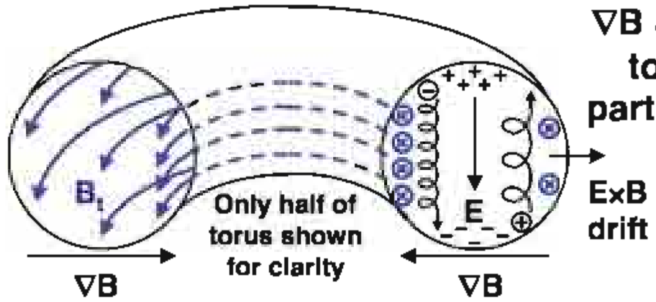

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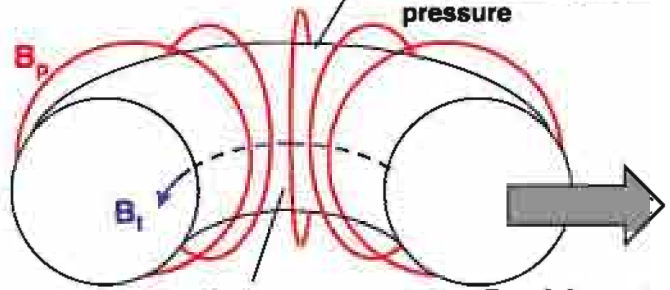
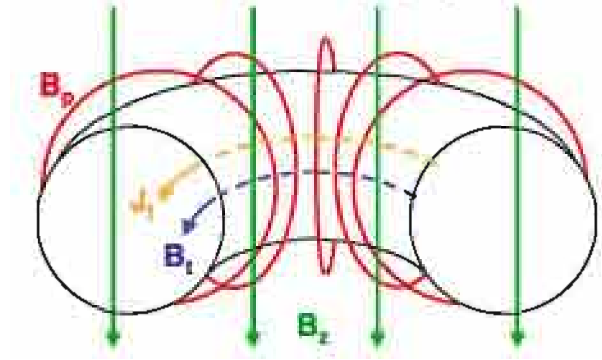


Problem 3: Net outward force on plasma

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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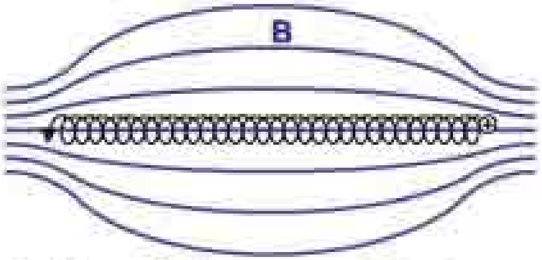

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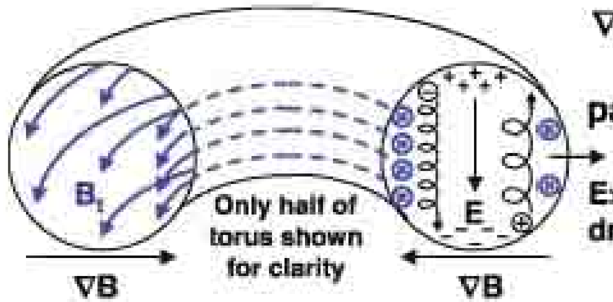

Goals (somewhat conflicting):

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

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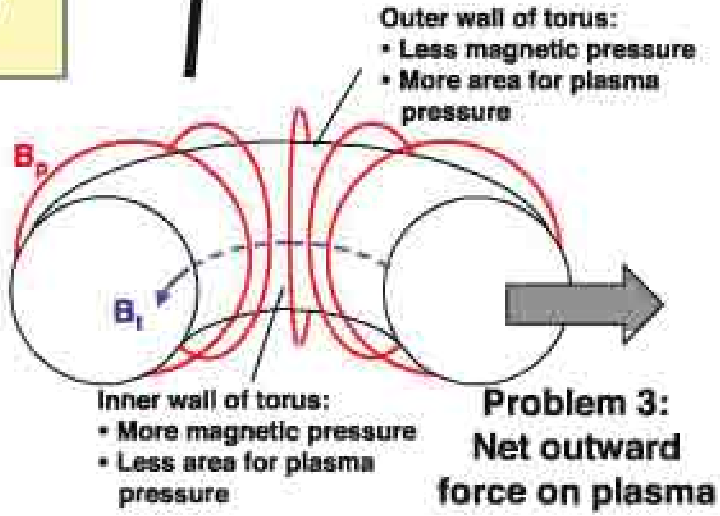
Solution 2: Add poloidal field B_p to mix particles in inner and outer regions of torus



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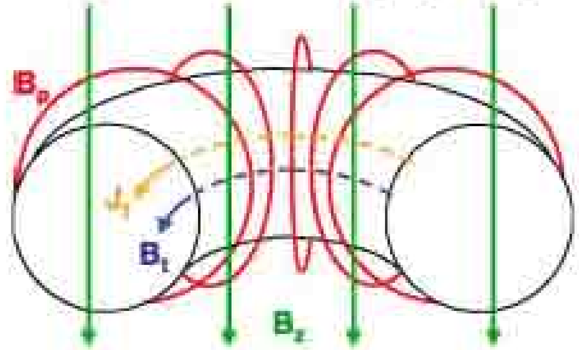
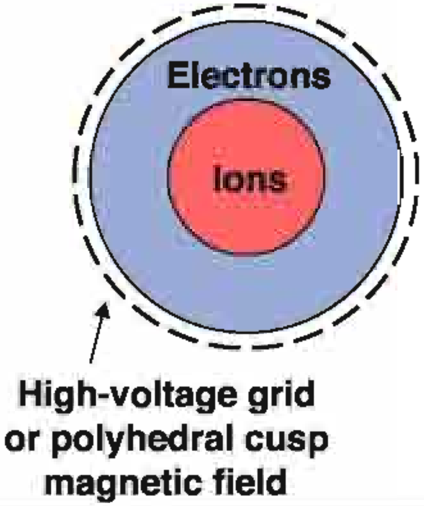


Other Confinement of Fusion Plasmas (1)

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 1995, *Phys. Plasmas* 2:1853 & 1873

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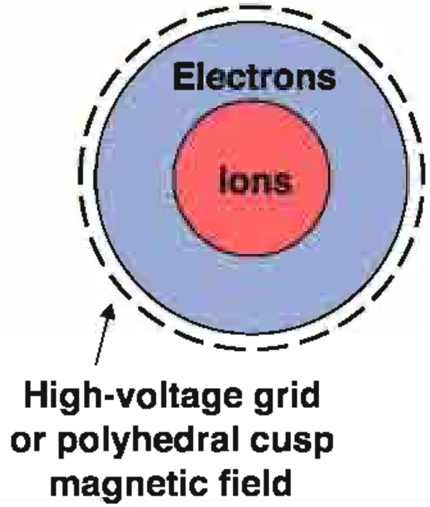

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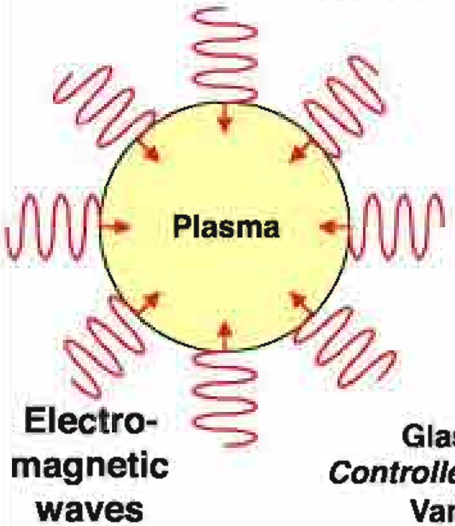

- Electromagnetic wave pressure confines plasma
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Glasstone & Lovberg 1960,
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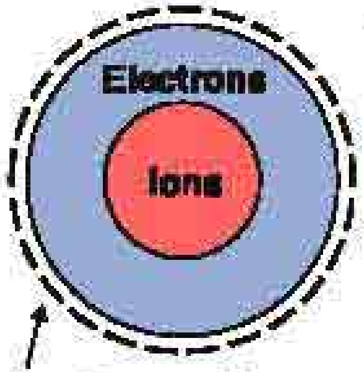

High-voltage grid or polyhedral cusp magnetic field

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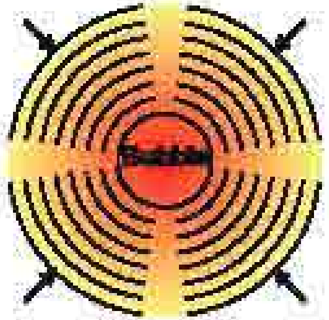
Acoustic: So No Fusion

Acoustic waves in deuterated acetone



- Acoustic waves in the acetone compress bubbles to fusion conditions??? Not replicated!
- Thermal conduction losses from heated region to surrounding liquid are prohibitive

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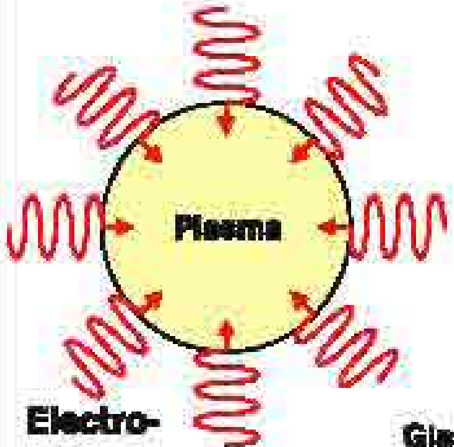

Electro-magnetic waves

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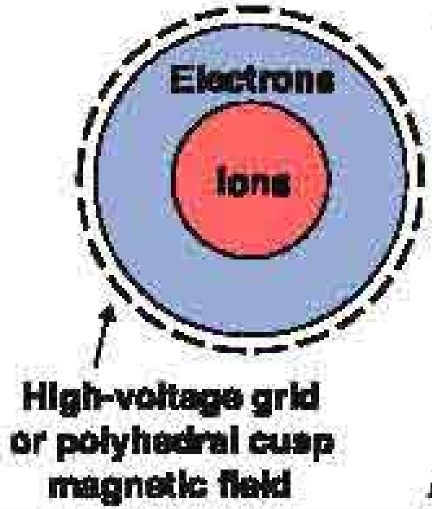

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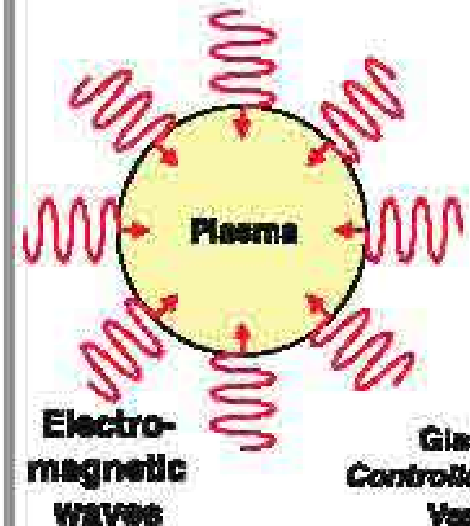

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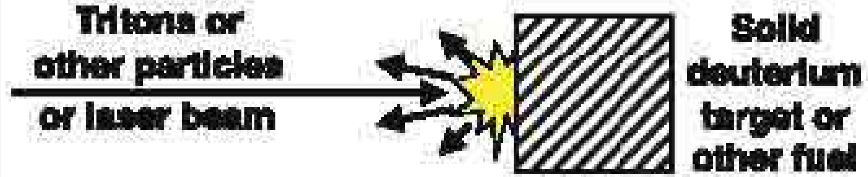
Beam + Solid Target

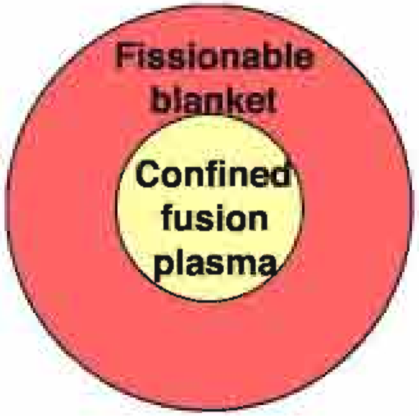


- Electrons in the target absorb and conduct away far too much of the beam energy for breakeven

Glasstone & Lovberg 1960, *Controlled Thermonuclear Reactions*, Van Nostrand, pp. 64-66

Other Confinement of Fusion Plasmas (2)

Fusion-Fission Hybrid



Has disadvantages of both fusion & fission:

- Fusion plasma requires expensive and complicated confinement system
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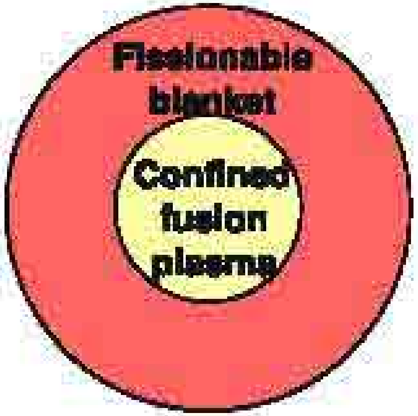

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Ball Lightning

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 1999, *Ball Lightning*, Kluwer/Plenum
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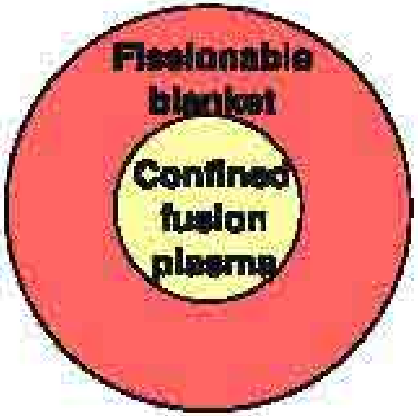

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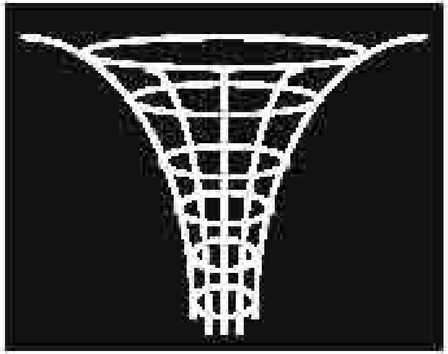
Small Black Hole

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

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

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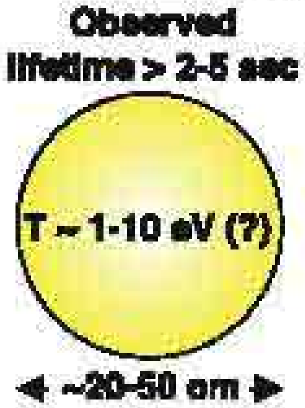

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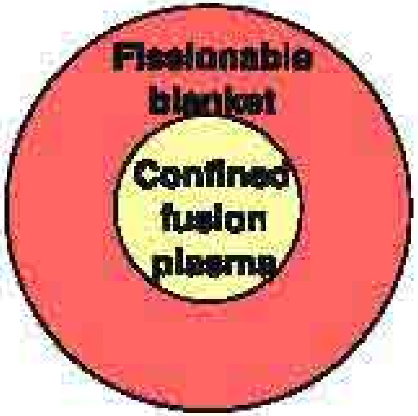

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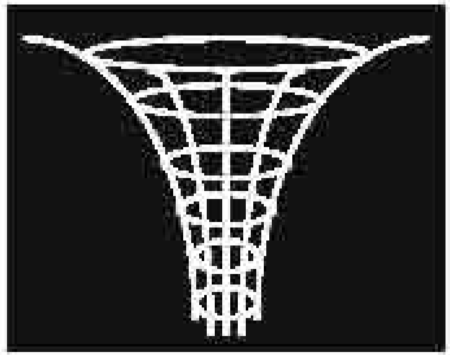

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- Are there other confinement approaches?
- Can one show that these ideas completely cover the phase space of confinement approaches?

Conversion to Electrical Energy

Heat

Carnot limit:

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

$$\sim 0.3 - 0.4$$

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

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

Conversion to Electrical Energy

Heat	Light nuclei (p^+, α, etc.)	
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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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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 ($^3He+^3He$, $p+^{11}B$, $p+^6Li$, etc.)
- Most high-efficiency direct electric converters

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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
- $D+^3He$ w/o product burnup: 30 MW 2.5-MeV neutrons, 500 MW X-rays, 1.8 GCi T
- $D+^3He$ with product burnup: 150 MW mainly 14-MeV neutrons, 500 MW X-rays
- Mainly thermal (Carnot-limited) conversion of fusion energy to electricity

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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)?**

Potential Thesis (or Nobel Prize) Topics

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- 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.

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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?
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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?**

More Potential Thesis (or Nobel Prize) Topics

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- 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 ^3He and cold D or hot p^+ and cold ^{11}B)?
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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?
- Are there any other confinement approaches worthy of investigation?

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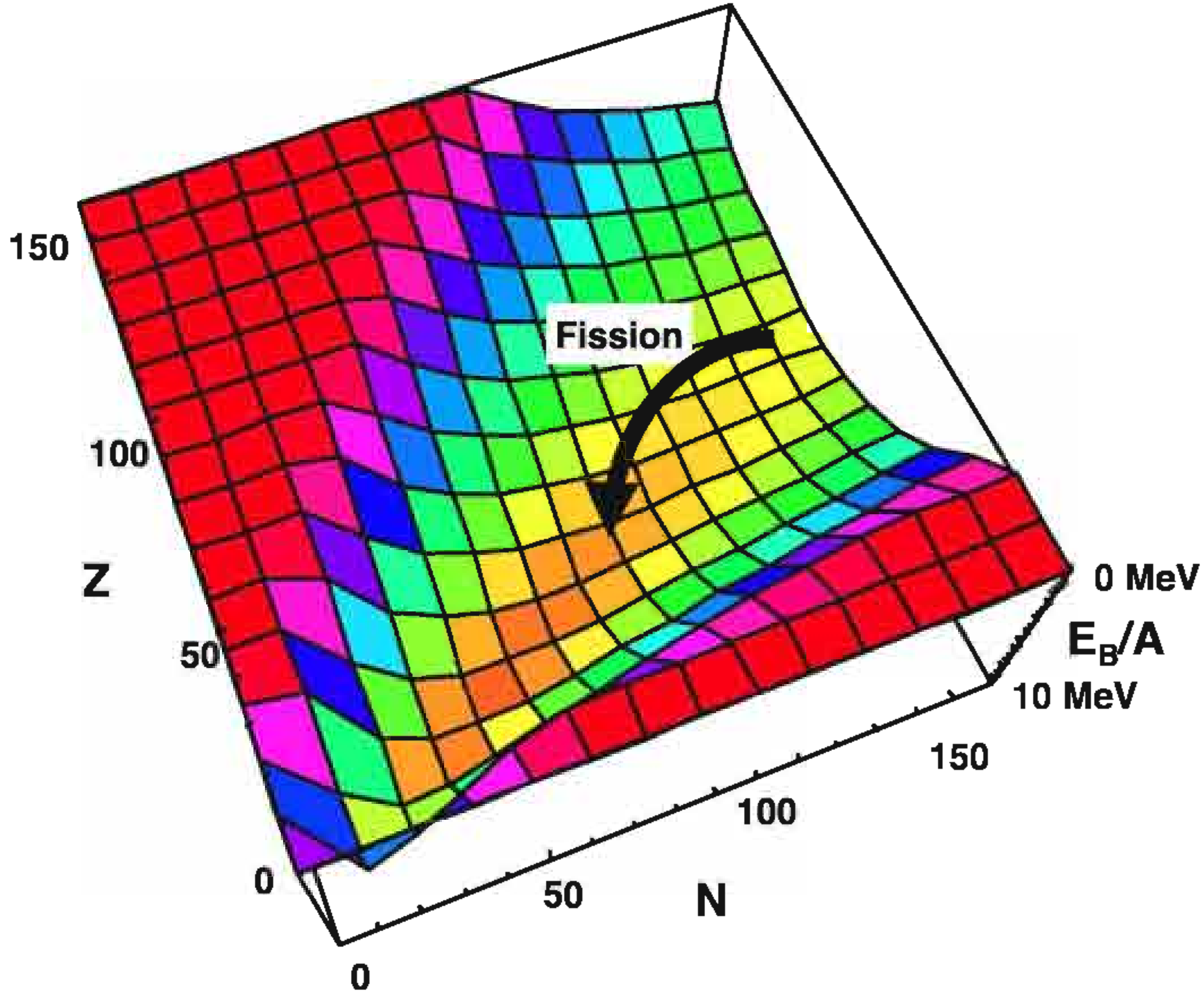
Conversion to electrical energy:

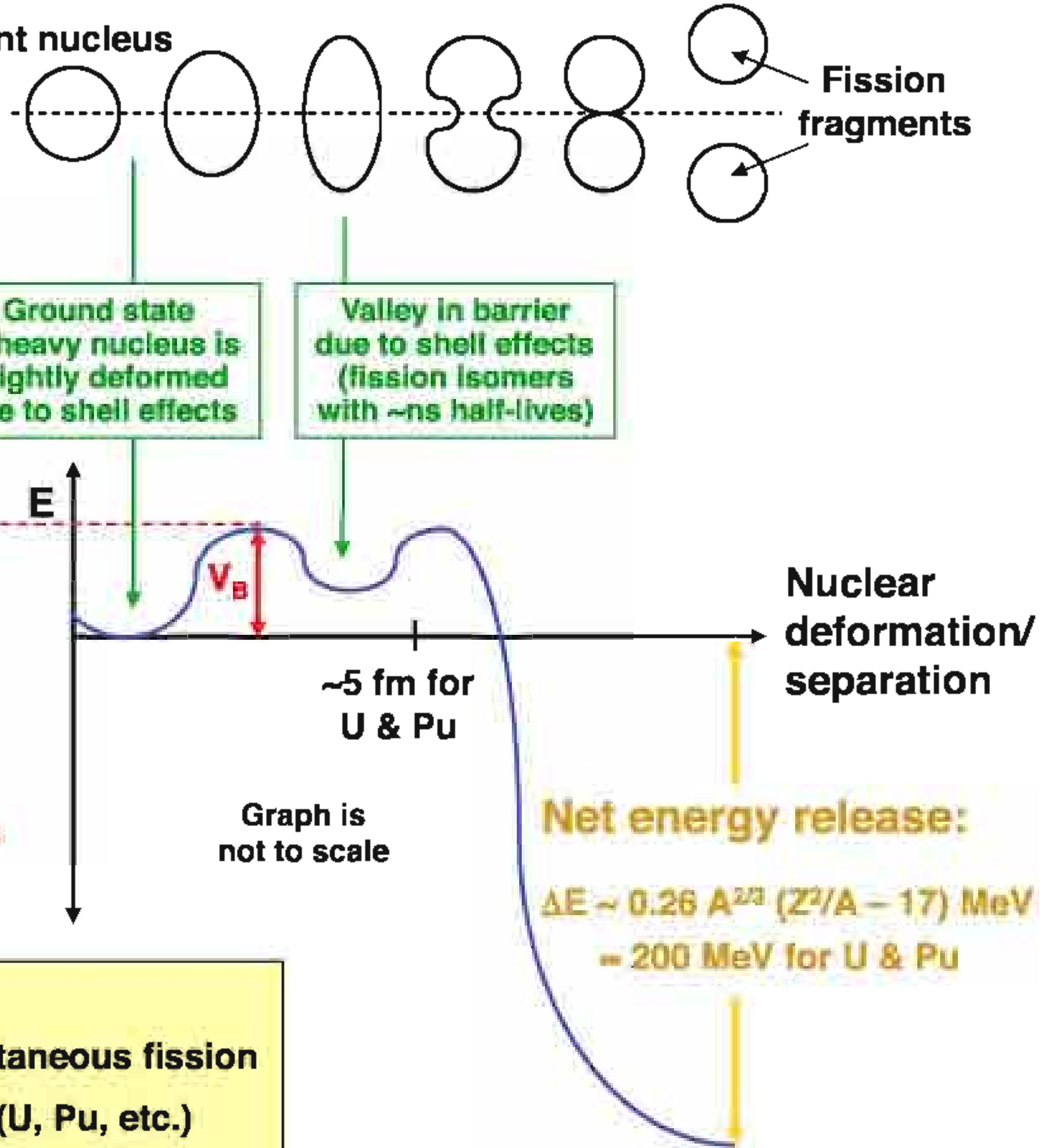
- What are the most efficient and/or most compact thermal-to-electric converters?
- What are the best converters for light nuclei—inverse linear accelerators, inverse cyclotrons, etc.?
- Are there practical ways to directly convert the energies of recoil nuclei or other heavy nuclei emitted by solid 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

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



Fission barrier height:

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

⬇

- 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
- $>3\times10^{8}$ 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 ($n + {}^{238}U \rightarrow {}^{239}U \xrightarrow{\beta} {}^{239}Np \xrightarrow{\beta} {}^{239}Pu$)
- $>4\times10^{10}$ 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 ($n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow{\beta} {}^{233}Pa \xrightarrow{\beta} {}^{233}U$)
- $>8\times10^{9}$ kg readily accessible to mining
  → $>8\times10^{6}$ GWe-years
  → >400 years of global consumption

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

^{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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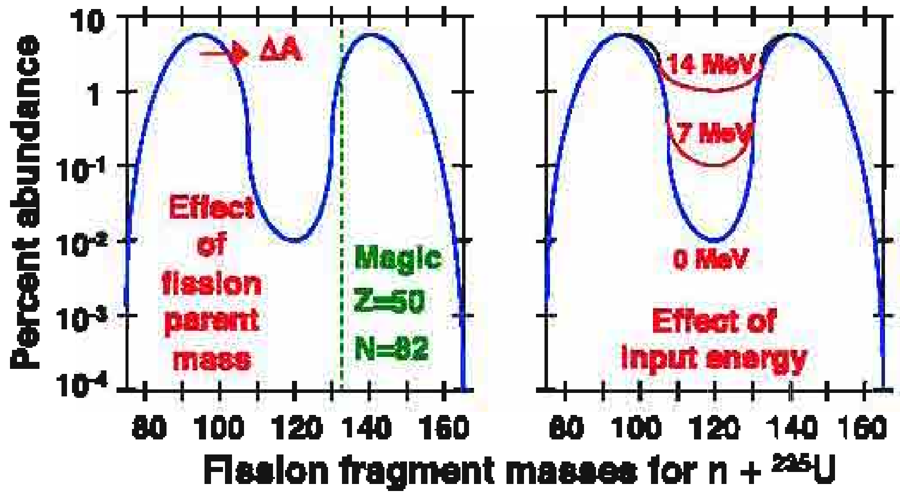
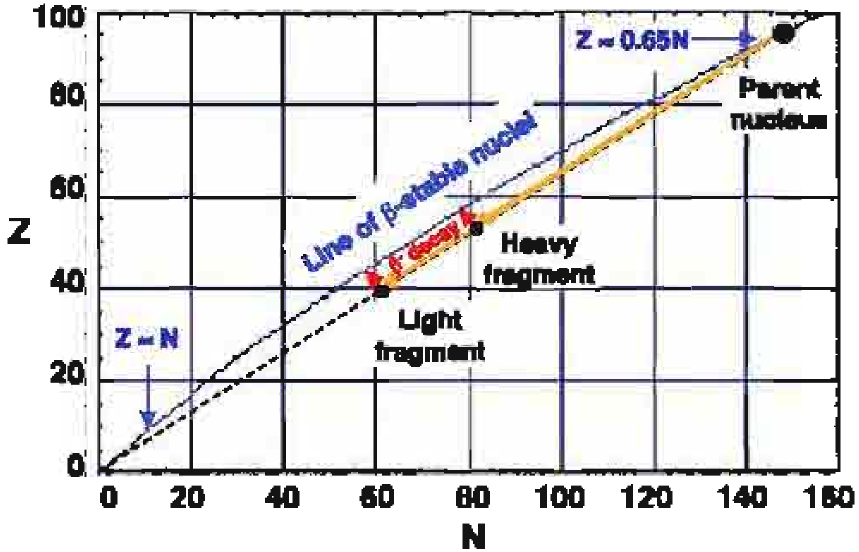
Fission Waste Production

Fission fragments

Asymmetric & wide range of fragments



Fragments must be β^- emitters



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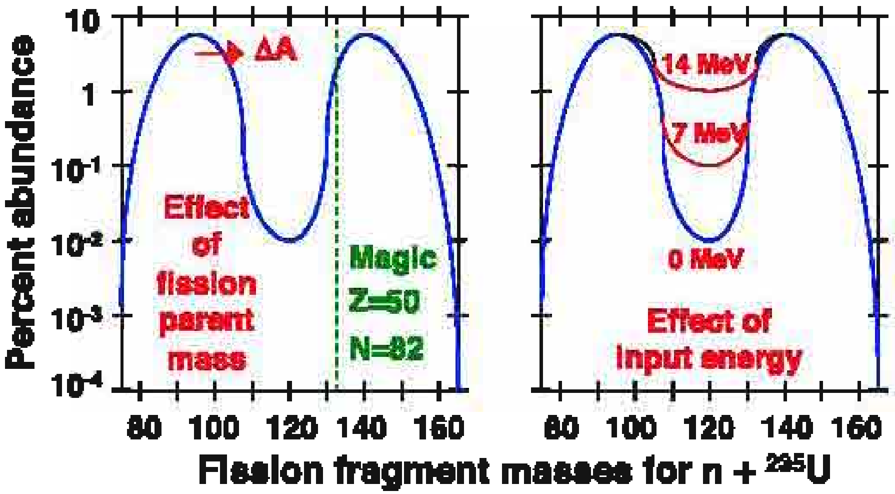
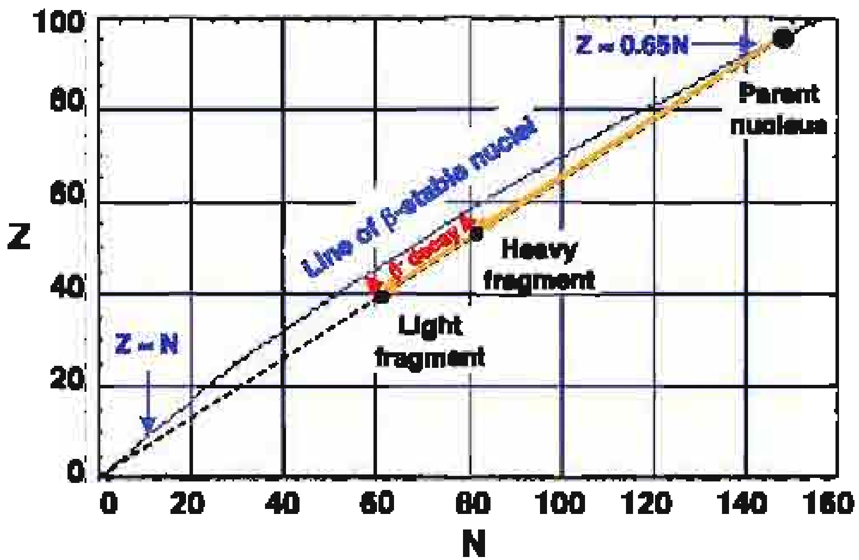
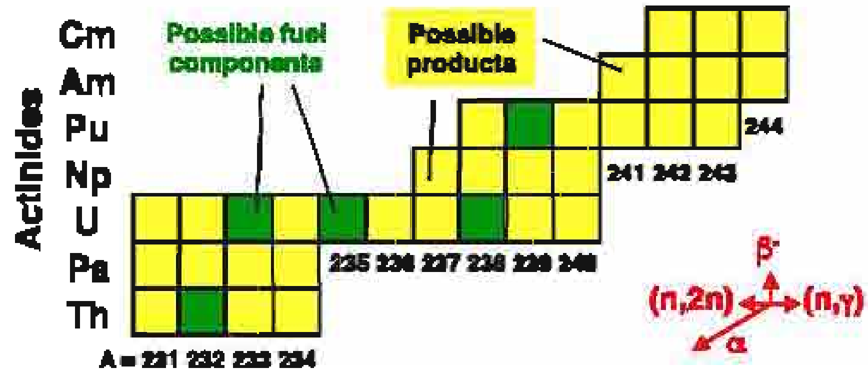


Fragments must be β⁻ emitters



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

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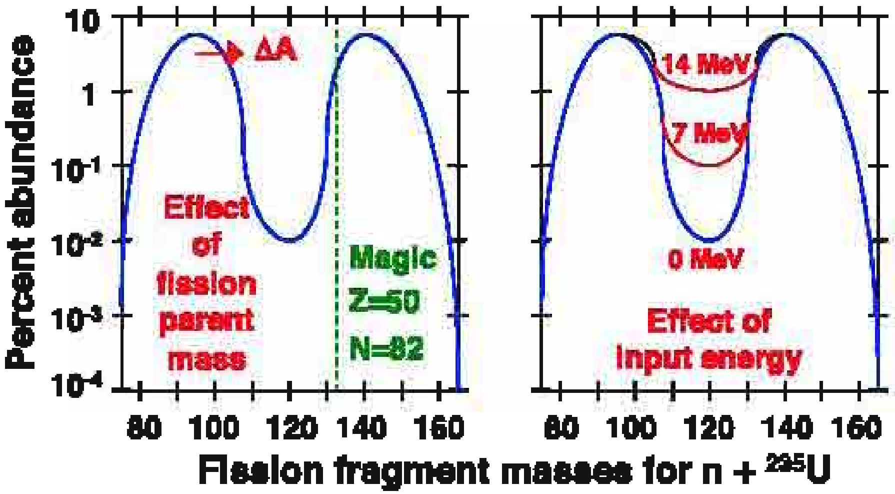

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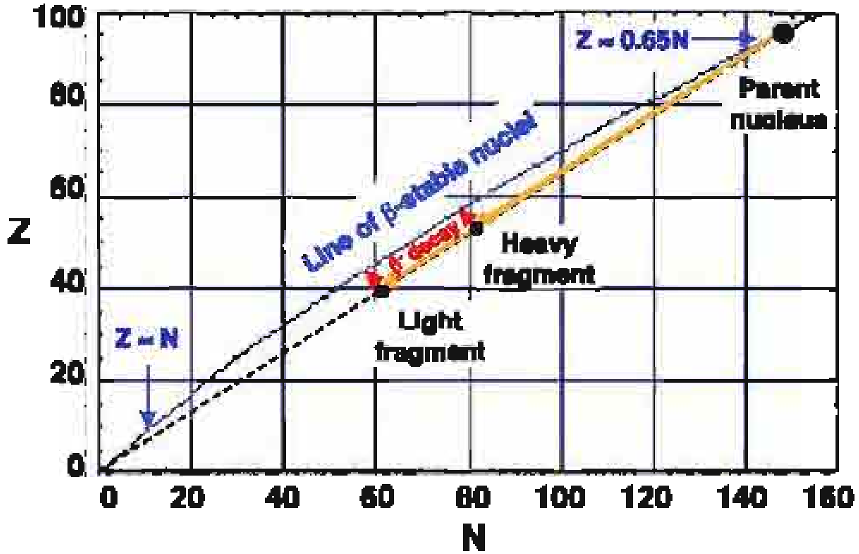

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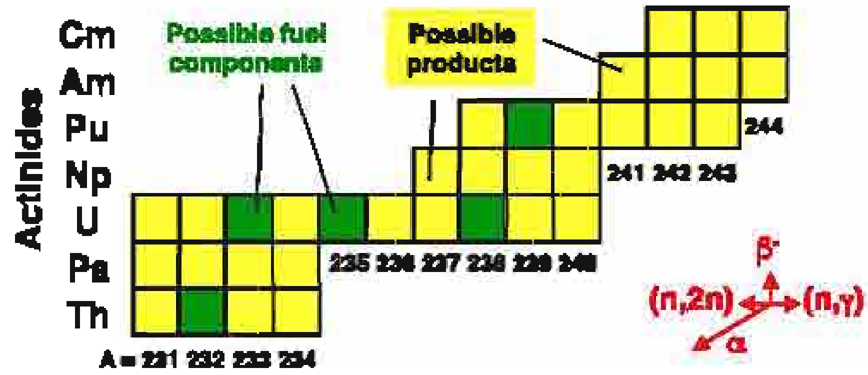

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Other neutron activation

Low-activation materials

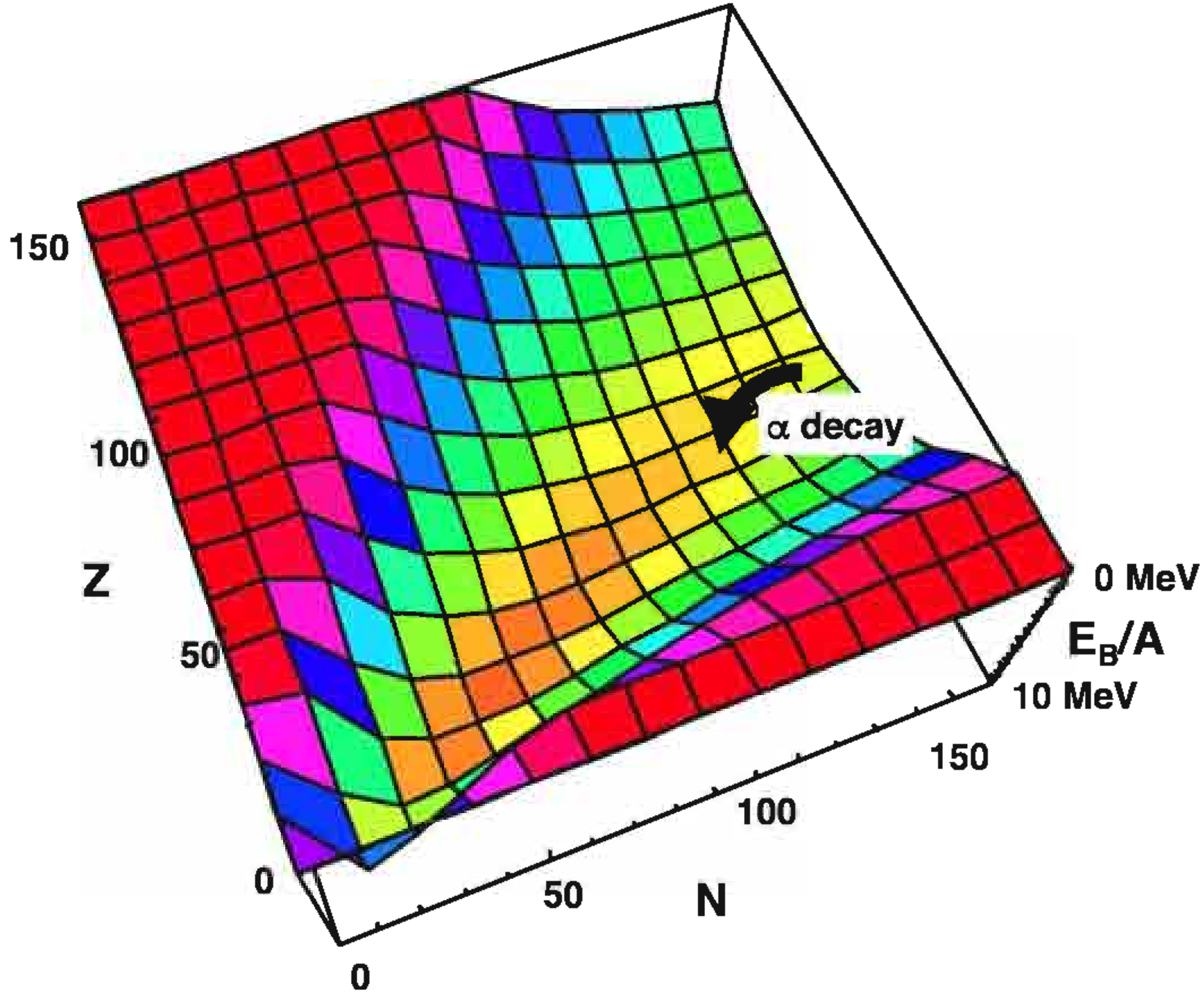
Moderators:	H_2O, D_2O, ^{12}C, etc.
Coolants:	H_2O, D_2O, ^{23}Na, etc.
Control rods:	^{10}B, ^{113}Cd, etc.
Reflectors:	^{9}Be, ^{12}C, etc.
Structural metals:	^{94}Zr, ^{98}Mo, etc.

- 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

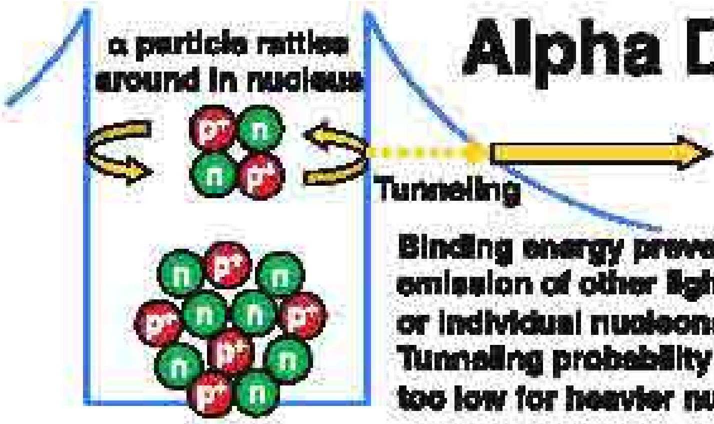
Fission Power

- 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.

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

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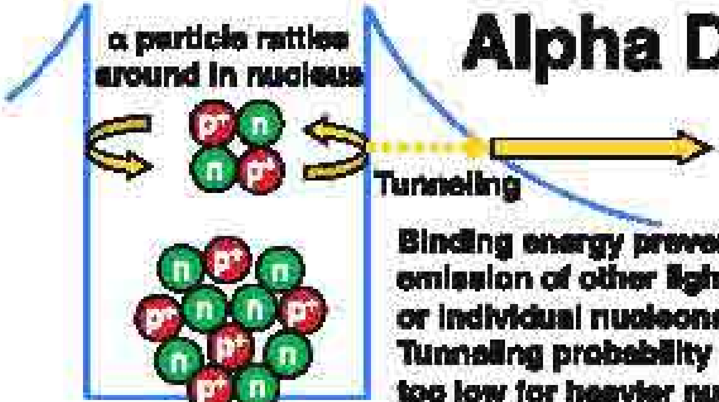

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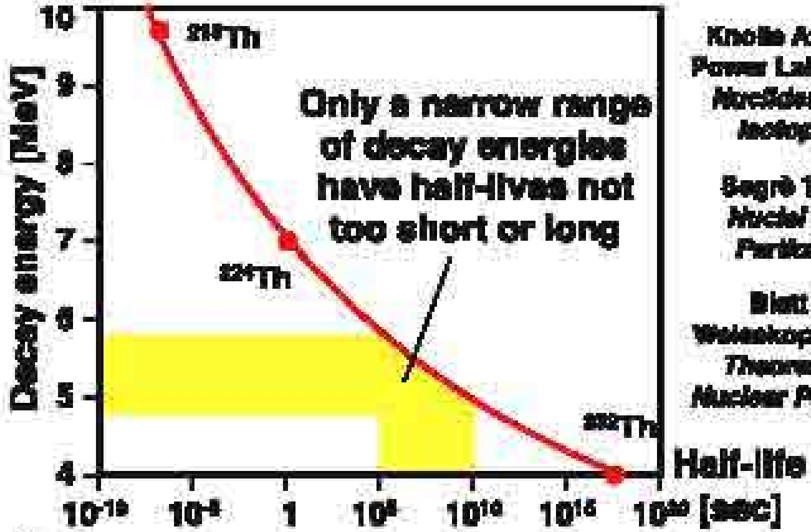

Knolls Atomic Power Lab 2010, *Nuclides and Isotopes.*

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	138 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
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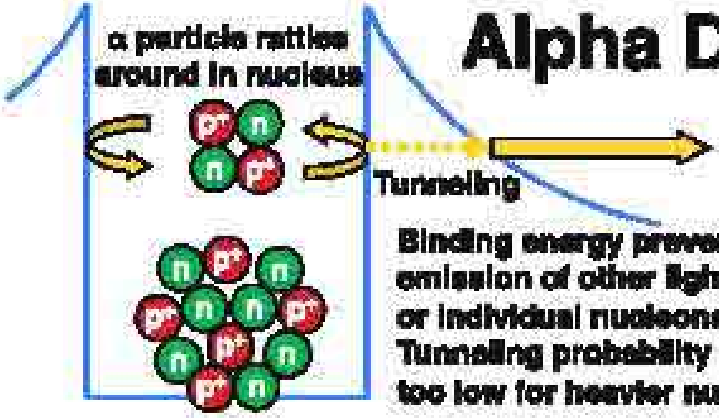

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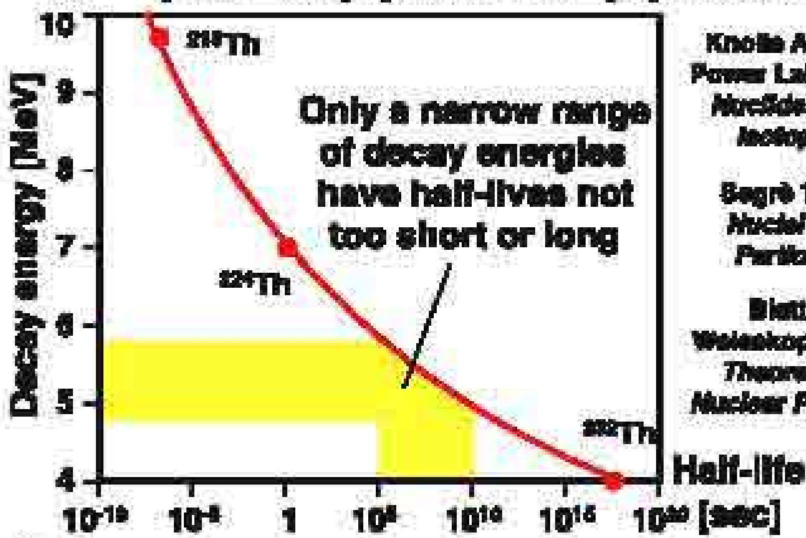

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1. Are there practical ways to use similar processes to make nuclei emit particles other than α particles (or β or γ)?

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?

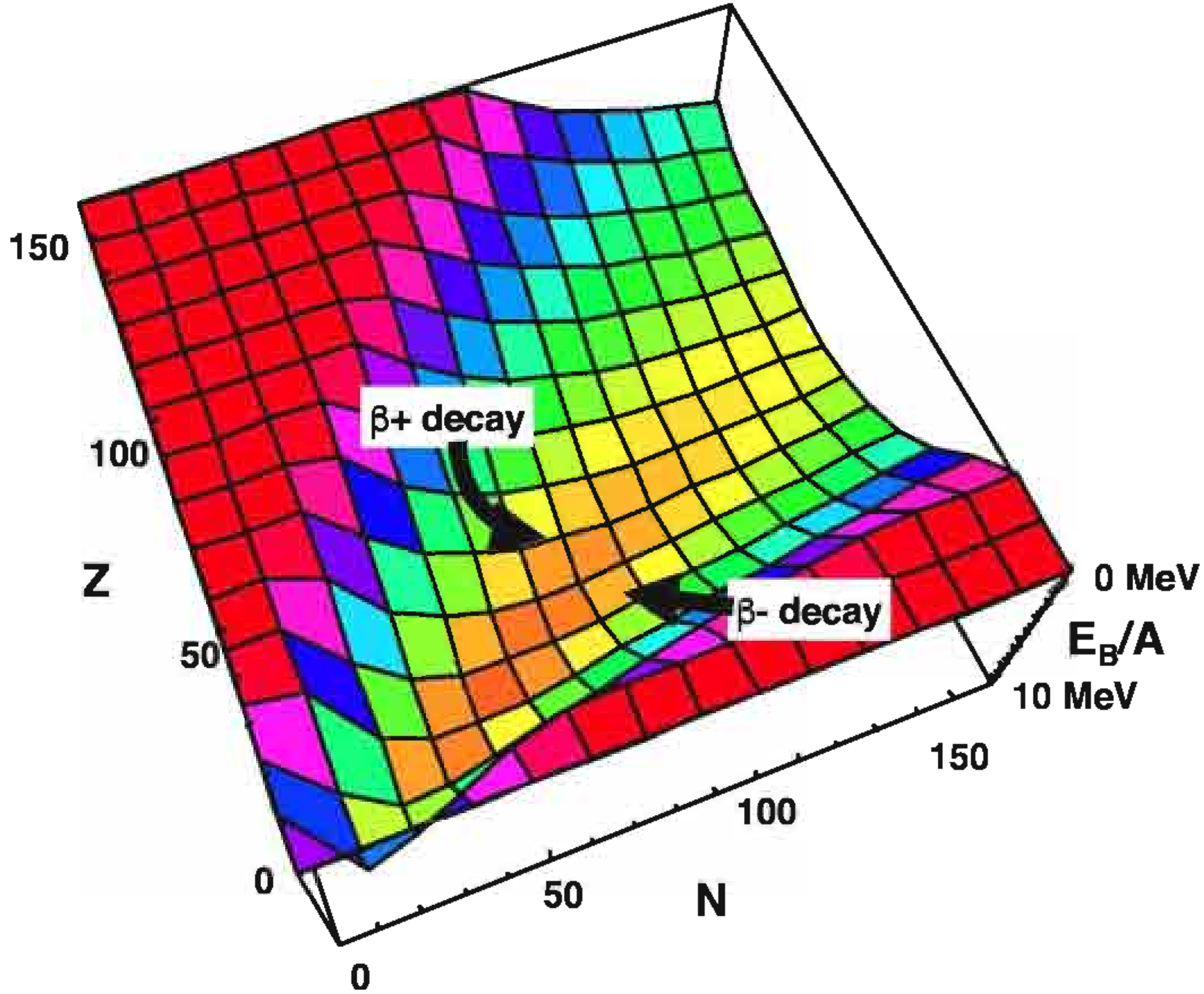
g. Electrostatic converters, inverse ion accelerators, etc.?

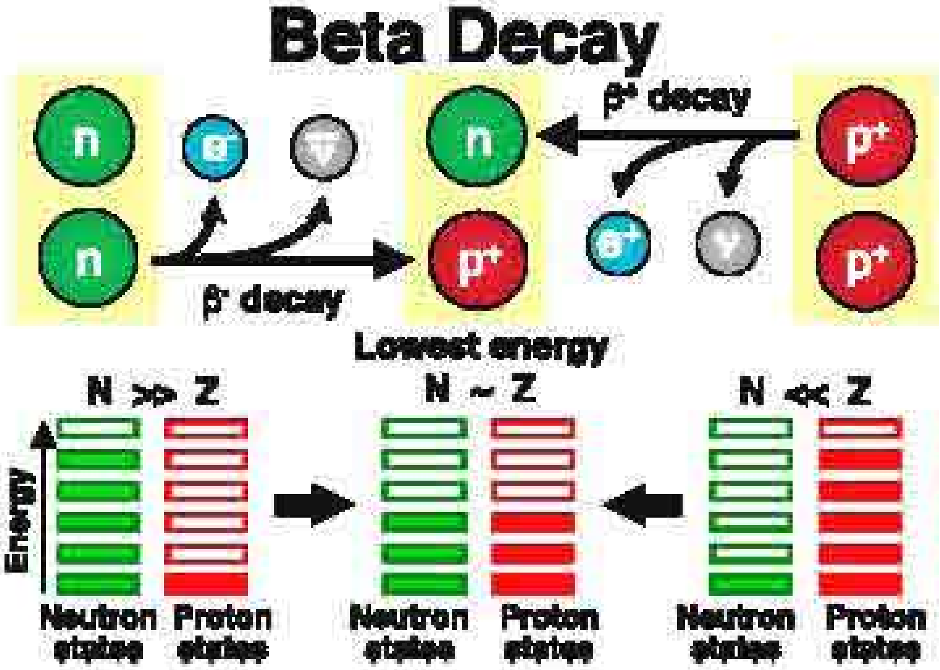
h. Are there other methods of conversion?

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-
ν̄
β- decay
n
p+
β+ decay
p+
p+
e+
ν
Lowest energy
N >> Z
N ~ Z
N << Z
Energy
Neutron states
Proton states
Neutron states
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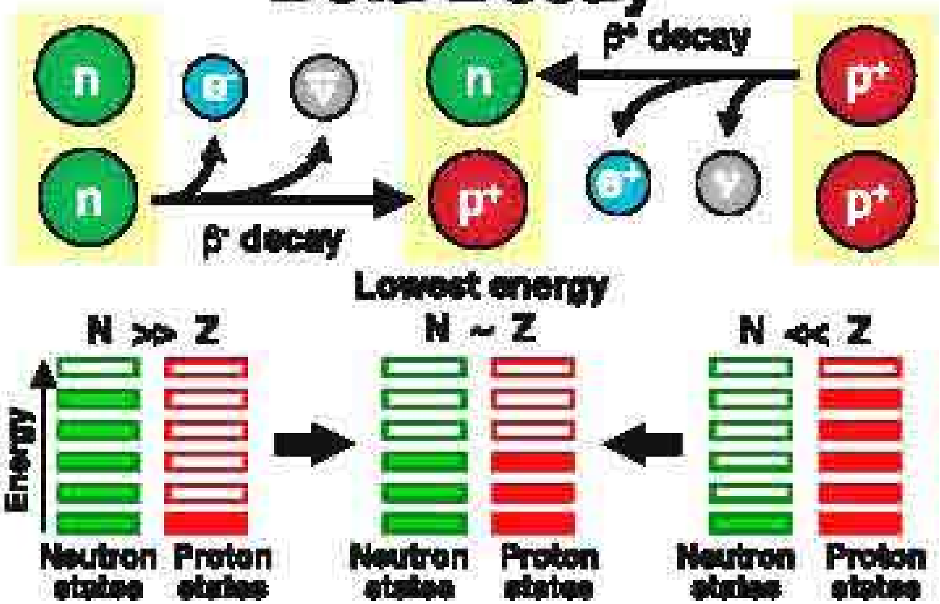


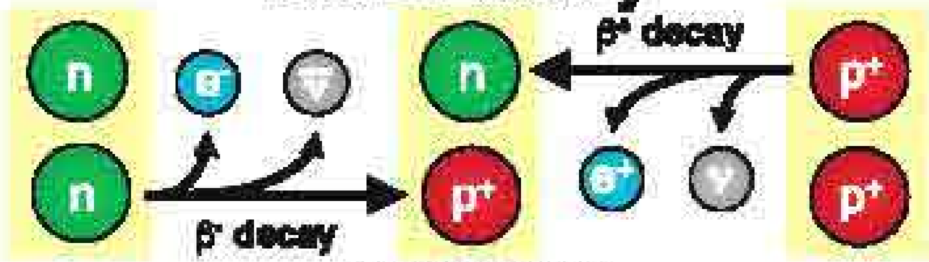
$$\tau_{1/2} \propto (10^4)^L \ (\Delta E)^{-4}$$

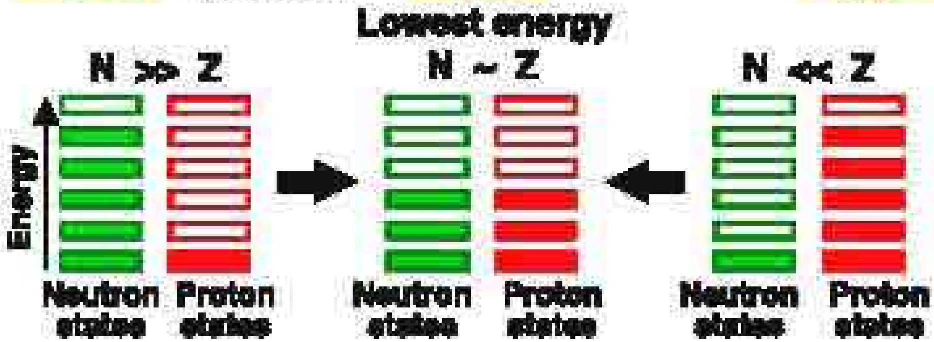
Some β emitters of interest

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





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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?

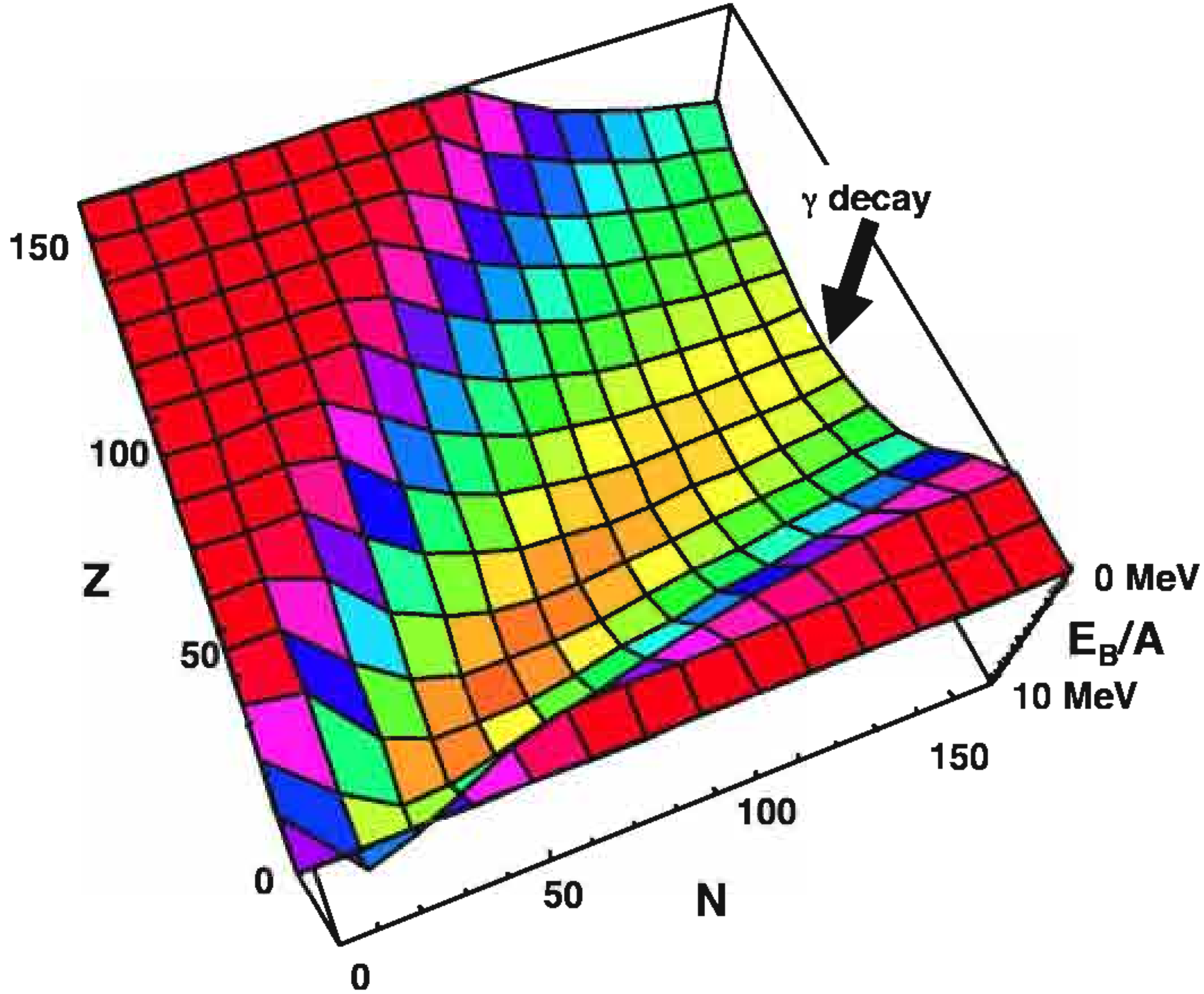
e. Could the β decay rate be increased by adding enough energy to the nucleus (via gamma rays, neutrons, or other means), then efficiently extracting that energy (plus the usual β decay energy) from the resulting β particle?

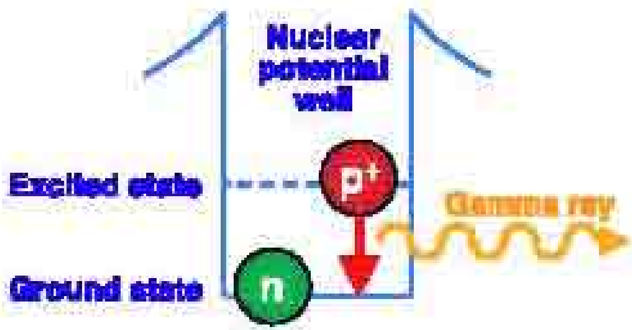
3. Are there better methods to convert the energy of the β particles to electricity?

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

$$\tau_{1/2} \propto (10^6)^{\Delta J} (\Delta E)^{-(2\Delta J + 1)}$$

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

Gamma Decay

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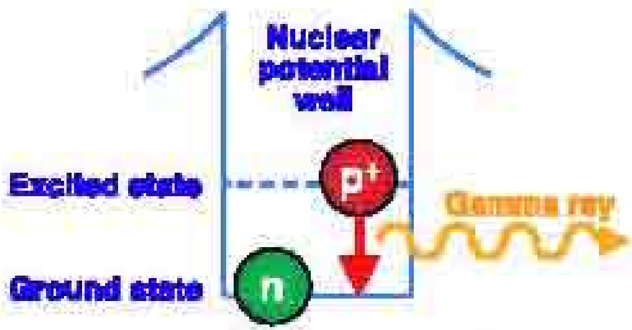
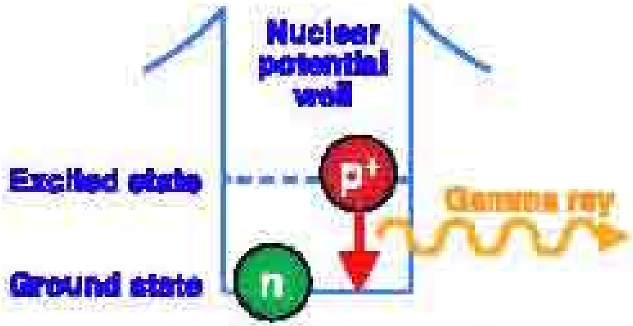


Some Isomers of Interest

Nucleus	Energy	ΔJ	Half-life
^{178}Hf	2.45 MeV	16	31 years
^{198}Au	812 keV	10	2.3 days
^{180}Ta	77.1 keV	8	>2x10^{16} yr
^{177}Lu	970 keV	8	160.4 d
^{182}Ta	520 keV	7	15.8 min
^{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
^{189}Os	30.8 keV	3	5.8 hr
^{60}Co	59 keV	3	10.5 min
^{163}Ho	298 keV	3	1.1 sec

Baldwin et al 1981, Reviews of Modern Physics 53:687. Baldwin & Solem 1997, Reviews of Modern Physics 69:1085. Bolte et al 1999, Gamma-Ray Lasers. Becker 2006, AIP Proceedings 819:1 [illegible]. Bollinger 2007, [illegible]. Brookhaven National Lab 2019, Nuclear Wallet Cards. Collins et al 1988, Physical Review C 37:2267. Collins et al 1999, Physical Review Letters 82:4:695. Collins et al 2000, Physical Review C 61:[illegible]. 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. Kilbuo 2007, [illegible]. Lewis et al 1997, JASON Report JSR-97-110. Litz & Merkel 2004, [illegible]. Pereira et al 2007, Laser Physics 17:6:874. Poppe et al 1992, UCRL-JC-109920-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 16:8:8.



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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?

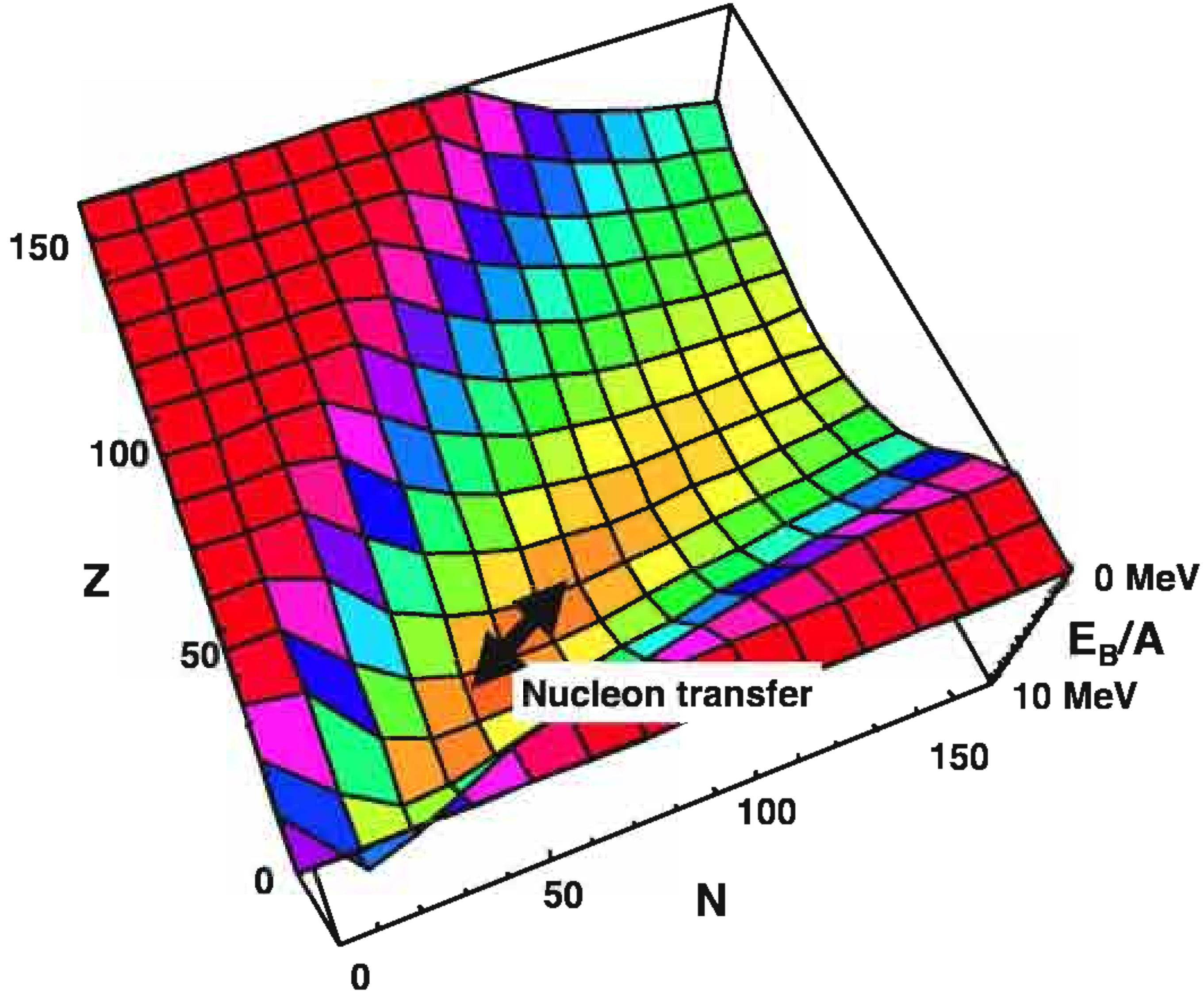
g. Could γ from one isomer decay induce the decay of other isomers?

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 1995, Gamma-Ray Lasers. Becker 2009, AIP Proceedings [illegible]. Bellows 2017, [illegible]. Brookhaven National Lab 2019, Nuclear Wallet Cards. Collins et al 1988, Physical Review C 37:[illegible]. Collins et al 1999, Physical Review Letters 82:[illegible]. Collins et al 2000, Physical Review C [illegible]. Collins et al 2001, Hyperfine Interactions 135:[illegible]. Collins et al 2005, Laser Physics Letters 2:[illegible]. Gsponer & Hurni 2009, Physical Principles of Thermonuclear Explosives. Hahn 1921, Naturwissenschaften 9:[illegible]. Hartouni et al 2008, LLNL-TR-[illegible]. Jain et al 2021, Nuclear Isomers: A Primer. Killus 2007, [illegible]. Lewis et al 1997, JASON Report JSR-97-110. Litz & Merkel 2004, www.[illegible].pdf. Pereira et al 2007, Laser Physics 17:[illegible]. Poppe et al 1992, UCRL-JC-[illegible]-Rev.1. Rivlin 2007, Quantum Electronics 37:[illegible]. 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:[illegible].

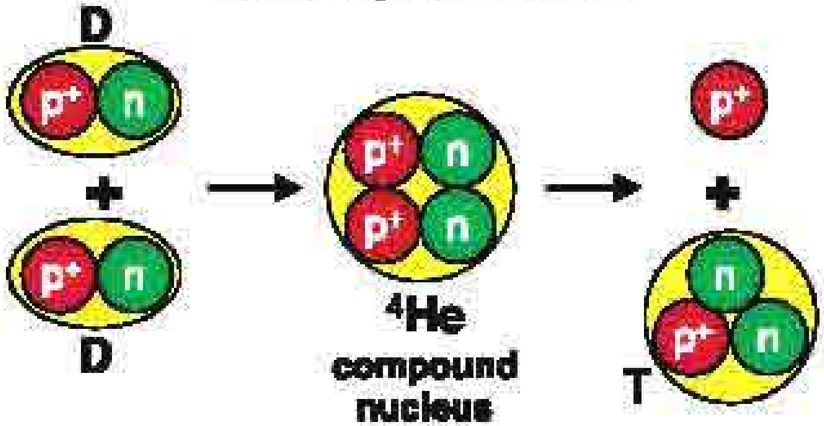
Binding Energy per Nucleon And Methods of Tapping It



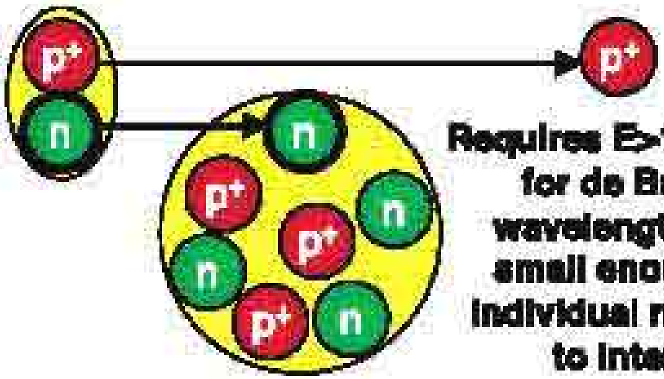
Nucleon Transfer Between Nuclei

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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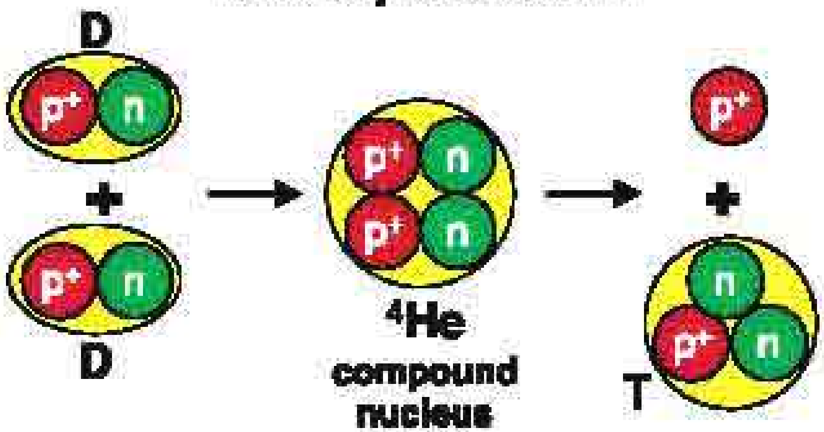

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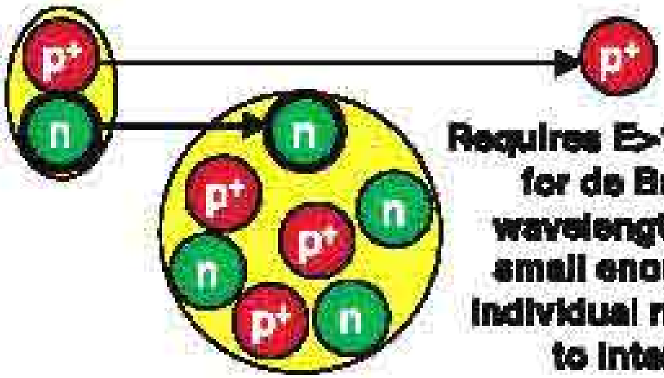

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Nuclei not in contact

Much easier to transfer neutrons than protons—no Coulomb barrier

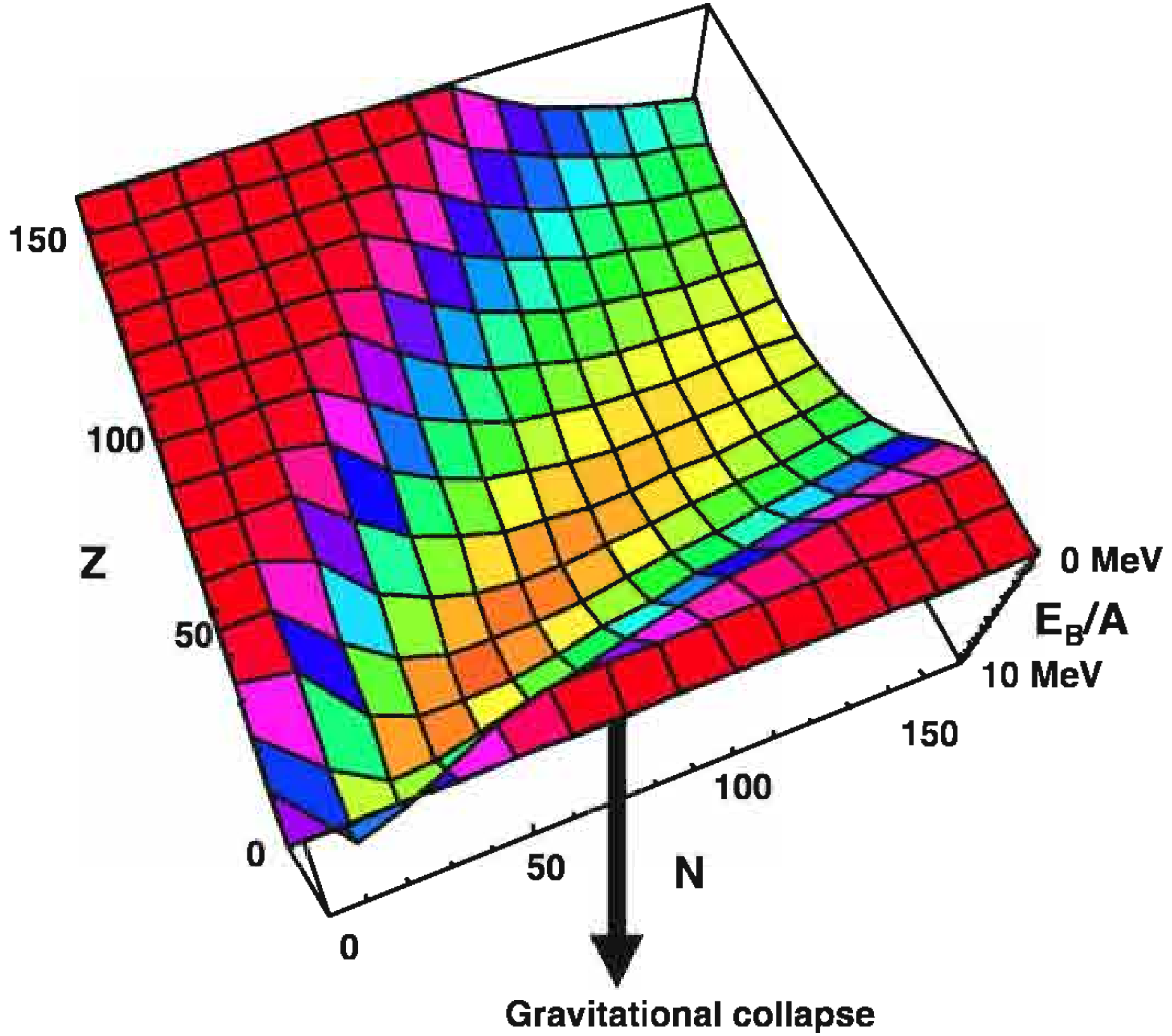
Difficult to supply input & remove output energy without fission

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.

Binding Energy per Nucleon And Methods of Tapping It



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: $r = R_s/2$:
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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:

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

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

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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:

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

$= 6.07\times10^{43}\, R_{s,\ meters}$ 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 4×10^6 Joules IR.)

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Particle Collider

Energy to create a black hole:

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

$= 3.79\text{x}10^{62}\ R_{s,\ meters}$ eV

Planck length—smallest size:

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

$= 1.62\text{x}10^{-35}$ meters

$R_s \sim L_P$ for smallest black hole:

$E \sim 6\text{x}10^{27}$ 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.

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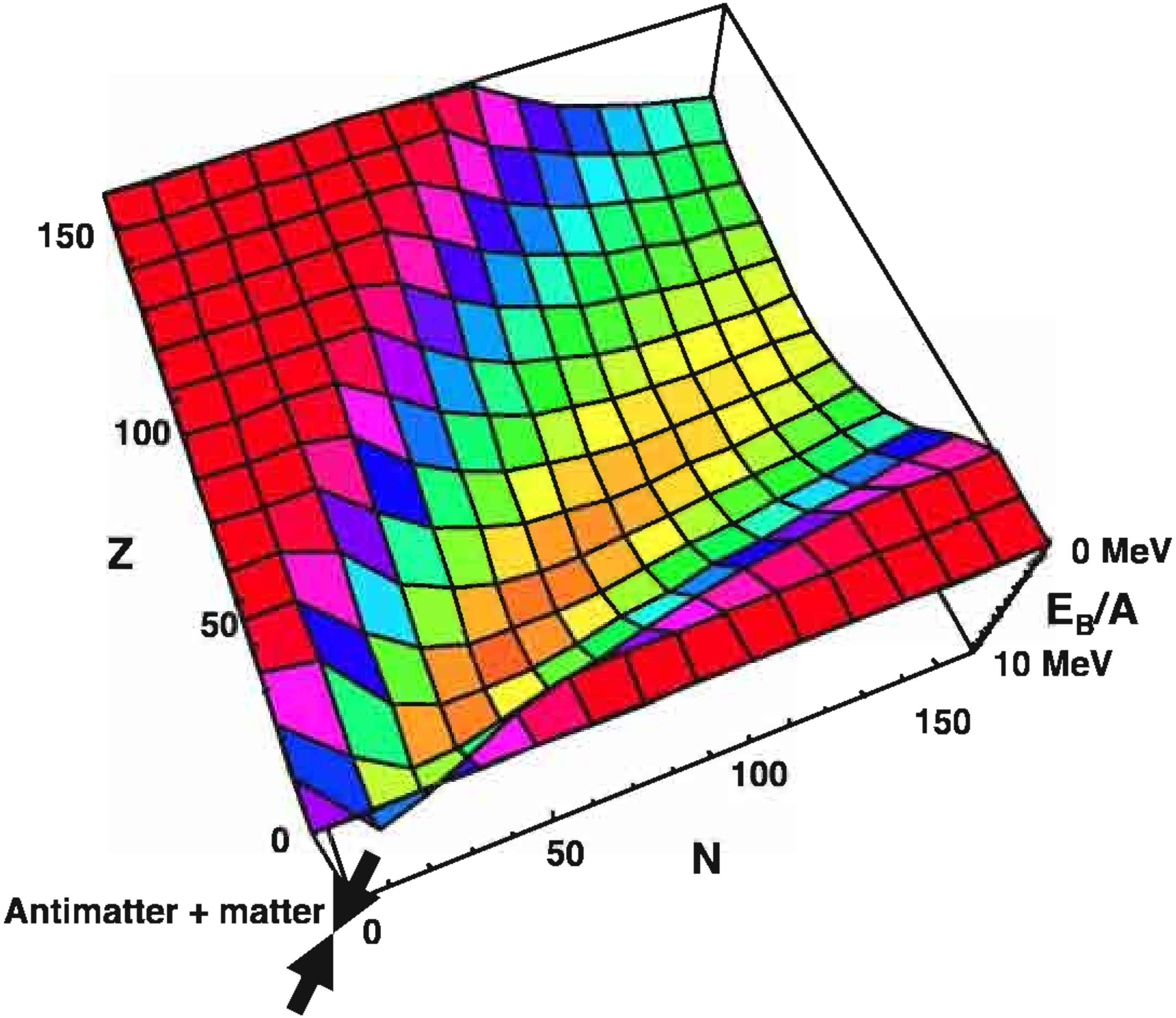

Antimatter

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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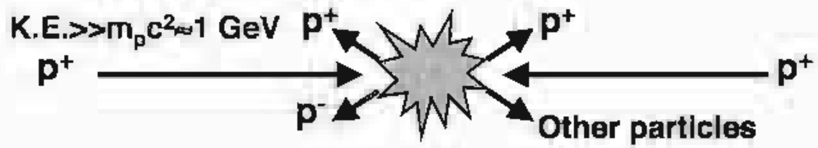
Production

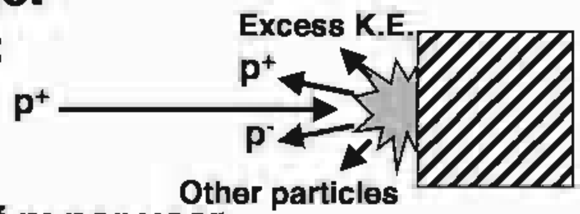
Much more difficult to make antiprotons (p^-) than positrons (e^+)

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

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