Fusion: Our Friend the Nucleus

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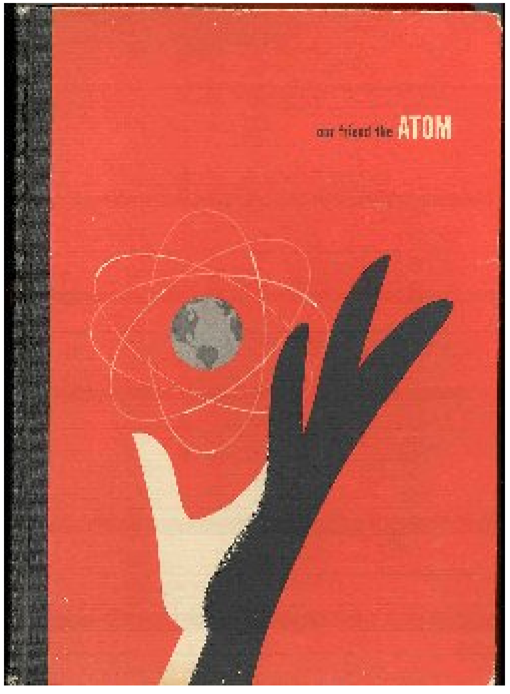
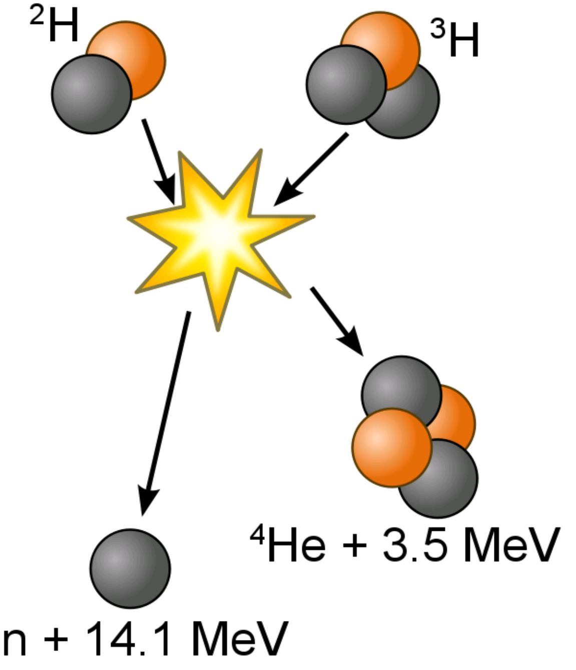


Our Friend the Atom: Disney film (1957)

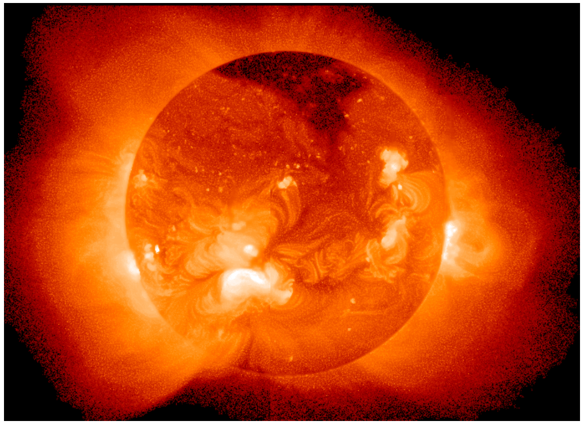


Deuterium-tritium fusion

Internet resources:
Wikipedia (of course)
fire.pppl.gov
fusedweb.llnl.gov
www.pppl.gov
lasers.llnl.gov
www.iter.org
hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html

Synopsys talk
Sunnyvale, CA
27 July 2009

Nuclear Menu

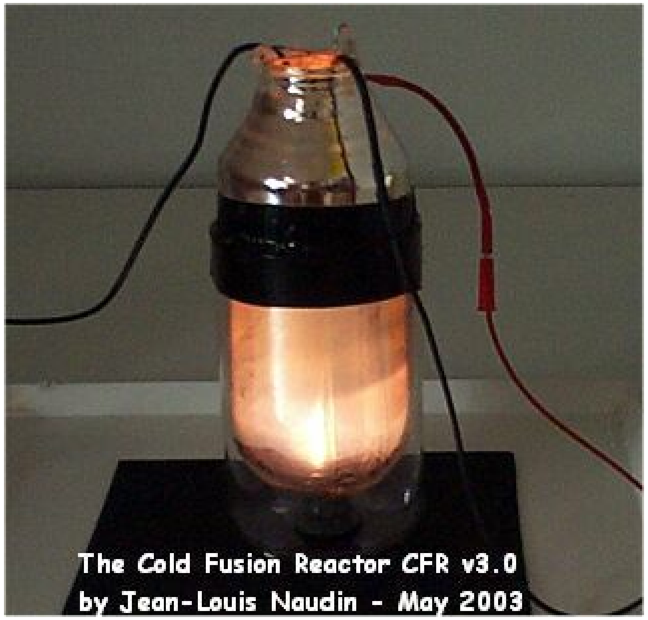


The Sun – very slow fusion

Fission power –
it works today

National Ignition Facility (LLNL)
inertial fusion

Tsar Bomba (Soviet nuclear test)
– very fast fusion!



Cold fusion?

Tokamak – magnetic fusion

Outline

I. Motivation – energy needs

II. Basics – I will not go into much detail here

* Binding energy: How nuclear reactions (fission and fusion) release energy

* Conditions for fusion – hot, dense, and confined plasma

III. Applications

* The Sun (gravitational confinement) – what it fuses, how it functions

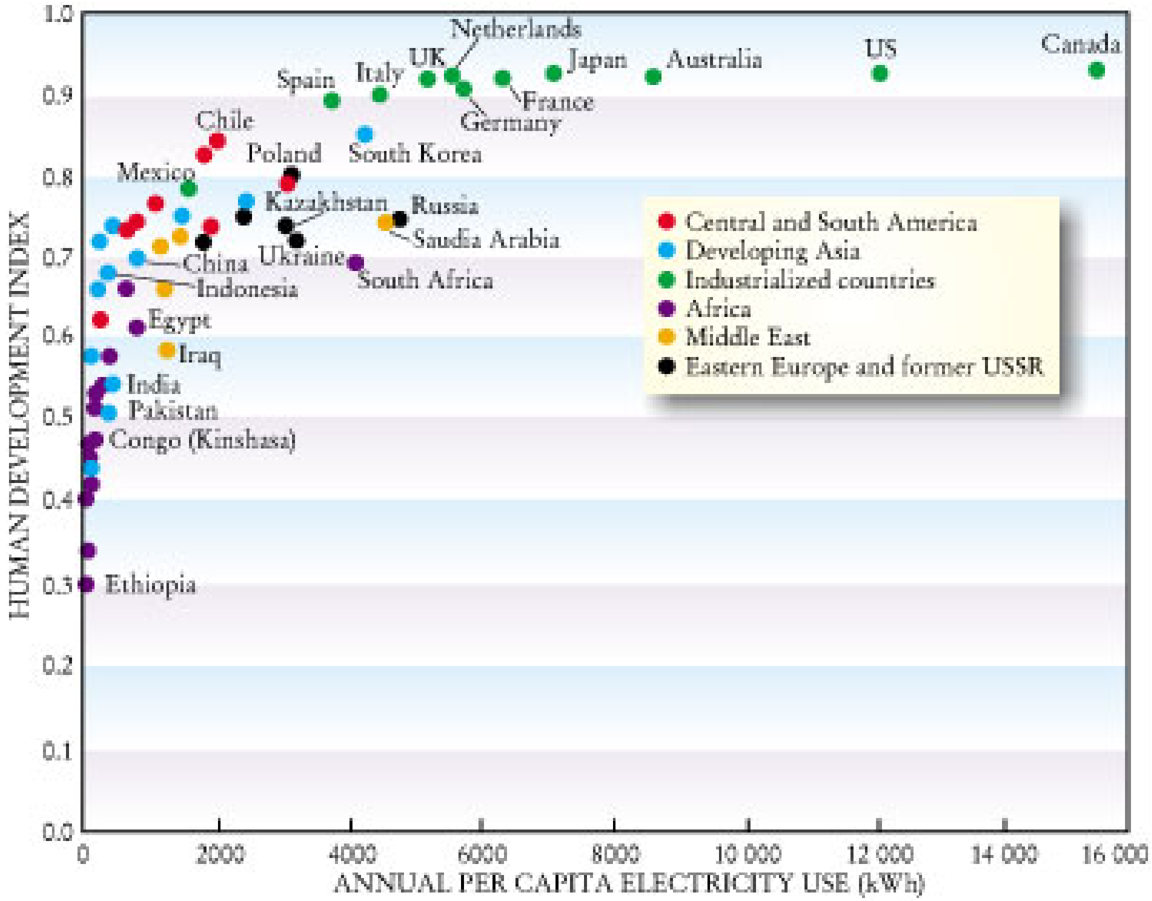
* Nuclear explosives – not covered here; they actually work

* Fusion energy schemes – don't work yet
  magnetic confinement
  inertial confinement

* Fusion development, big picture things.

Energy and human well-being

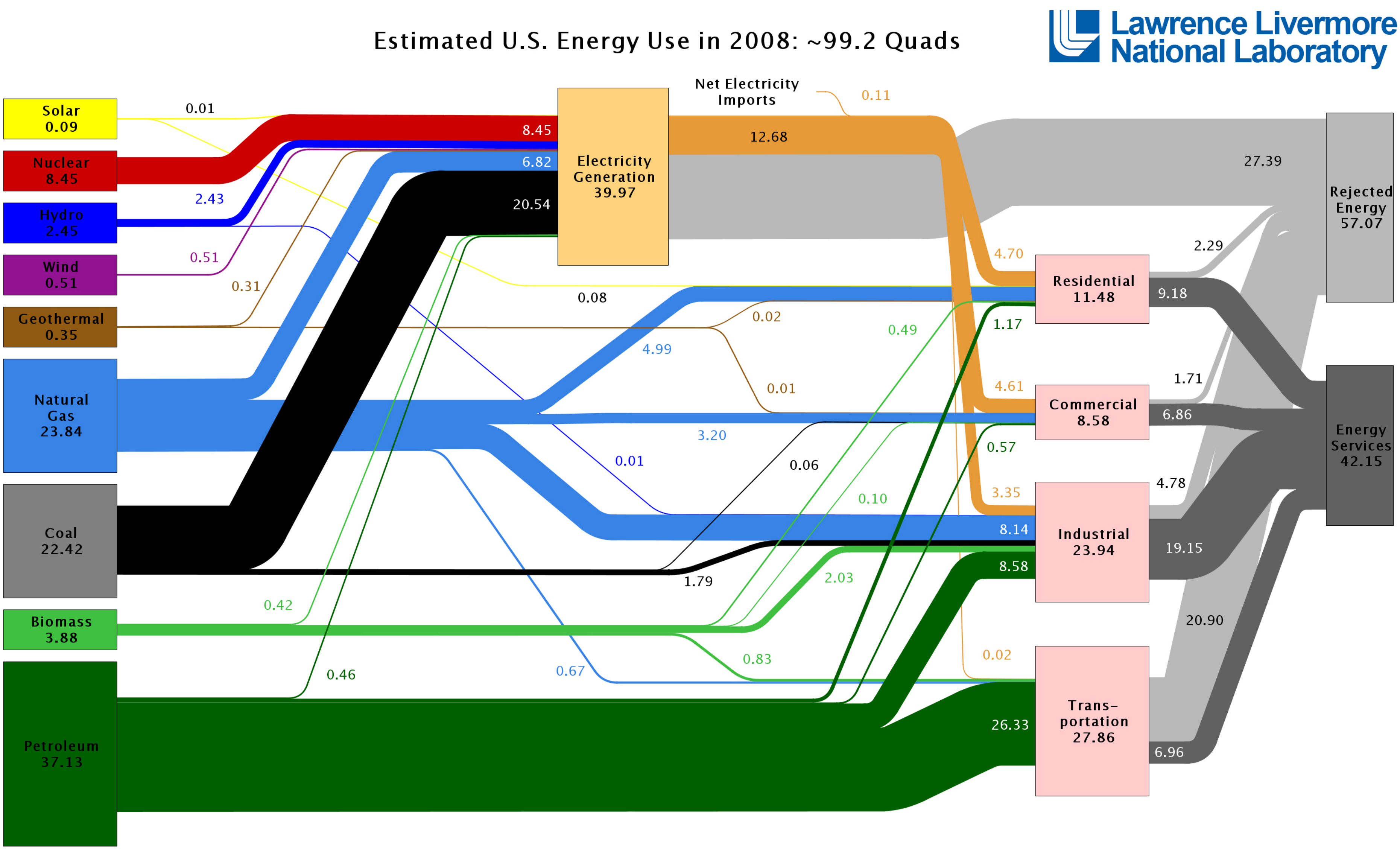
Quality of life: linear or log, e.g. Richter, scale???



Electricity use per person

USA: per person, we use
12,000 kilowatt * hours / year = 1.38 kilowatts (about 14 100-watt lightbulbs)

USA energy use 2008



Source: LLNL 2009. Data is based on DOE/EIA-0384(2008), June 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Renewables: biomass + geothermal + wind + hydro + solar = 7.28

Nuclear (fission): 8.45

Forms of energy

Universe consists of **substances** (matter, light, gravity,...). **Energy** is a *property* of substances.

Normal matter: made of massive particles; take one particle with mass m:

Matter energy: $E_{mat} = E_{mass} + E_{kin}$

Mass energy: $E_{mass} = m * c^2$ thus saith Einstein! More later

Kinetic energy: $E_{kin} = (\gamma-1)\, m * c^2$ $\gamma = [1 - v^2/c^2]^{-1/2}$ v = particle speed c = speed of light

$\approx (½)\, m * v^2$ Newtonian physics; (speed v much less than c)

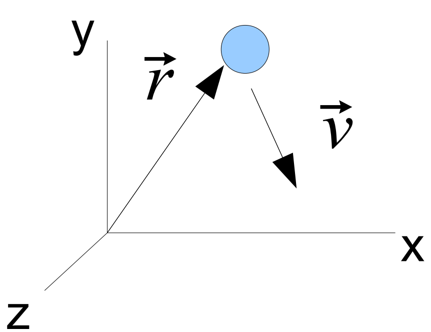
Fields: gravity, electric and magnetic (e.g., light): generally massless, but possess energy, called field energy.

Matter energy (mass + kinetic) NOT conserved: drop a rock, the rock and Earth gain kinetic energy.

Potential energy: depends on the arrangement of matter, so that matter energy + potential energy is conserved. Potential energy is not just a mysterious mathematical trick, but is the field energy!

- They usually don't tell you this in high school...

Consider a ball or yo-yo being twirled around your head at a constant speed. Its position is changing, and so is its velocity. BUT, its speed and kinetic energy are constant!



position: $\vec{r} = (x, y, z)$ speed: $v = \sqrt{v_x^2 + v_y^2 + v_z^2}$

velocity: $\vec{v} = (v_x, v_y, v_z)$ $v_x = \dfrac{\Delta x}{\Delta t}$, v_y, v_z *similar*

acceleration: $\vec{a} = \dfrac{\Delta \vec{v}}{\Delta t}$ Force: $\vec{F} = m\vec{a}$ m = mass

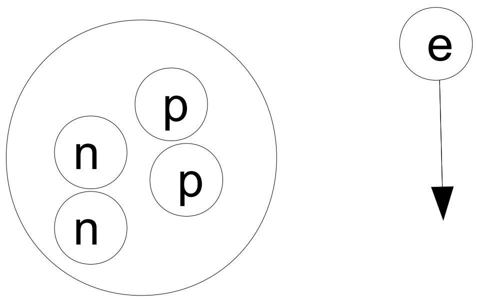
The four forces, atoms and nuclei

Four basic forces of nature:

- Strong nuclear: produced by quarks, which make up protons and neutrons.
- Electromagnetic: produced by electrical charges such as protons (+) and electrons (-).
  Like charges repel, opposites attact.
- Weak nuclear: involved in, for example, the decay of the neutron.
- Gravity: unimportant on atomic scales; important in planets, stars, the universe.

Atom: consists of several electrons surrounding a very small, heavy, nucleus

Electrons (- charge) and protons (+ charge) drawn together (but not right on top of each other, due to quantum mechanics).



Nucleus: made of protons and neutrons, much smaller than the atom

Protons in the nucleus repel electrically, so why does the nucleus hold together?
Answer: the strong nuclear force!

An isolated neutron is unstable due to the weak force! Half-life of 10.2 minutes!
Stable inside a nucleus.

The nucleus is a bizarre, co-dependent, nearly dysfunctional family:
Protons would fly apart without neutrons. Neutrons would decay without protons nearby.

$E = mc^2$ Explained: Binding Energy

The energy of a composite system is the same whether the system is viewed as a single units or as a collection of parts.

This is not true for mass!

Mass = inertia; resistance to acceleration = force / acceleration

How does the mass of a composite system relate to the mass of it parts?

Take a system at rest ($E_{kin,sys}$ =0) and isolated ($E_{pot,sys}$ =0).

$$E_{sys} = m_{sys} c^2 = \sum_i E_{part,i} = \sum_i \left(m_i c^2 + E_{kin,i} \right) + E_{pot}$$

$$m_{sys} = \sum_i m_i - m_{bind}$$

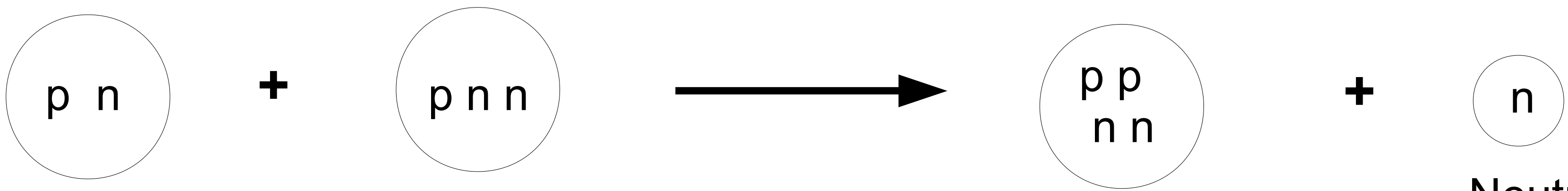
$$m_{bind} c^2 = E_{bind} = -\sum_i E_{kin,i} - E_{pot}$$

"binding energy" or "mass defect"

For a system to be bound together, the potential energy must exceed kinetic energy or it would fly apart! So E_{bind} is positive!

All systems have binding energies: atoms, molecules, the solar system, galaxies, but usually it's much less than the rest energy ($m*c^2$).

DT fusion: a VIP (very important process)



Deuteron (D)
Bind. En. 2.23

Triton (T)
Bind. En. 8.48

Helium-4 (α)
Bind. En. 28.3

Neutron
No Bind. En.
(that we care about)

Deuteron = deuterium nucleus; stable; naturally occuring (1/6500 of terrestial hydrogen)
"heavy water" = $D_2 0$

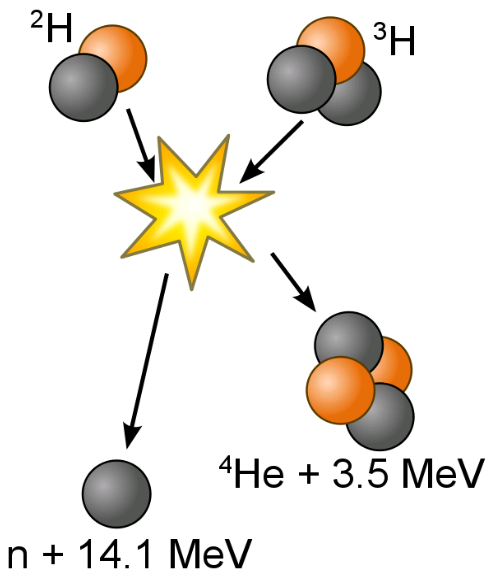
Triton = tritium nucleus; unstable (half-life of 12.3 years); trace amounts on Earth;
Can be produced from lithium: Li6 (3p, 3n) + n $\rightarrow \alpha$ + T

Binding energies in MeV = million electron-Volts.

Chemical reactions involve ~ 1 eV per electron exchanged:
it takes 13.6 eV to ionize hydrogen.

Note: Deuterium-tritium fusion is the easiest to achieve, but the tritium must be produced in the reactor since it does not occur naturally. This can be done by a reaction involving a fusion neutron and a lithium nucleus.

Energy released in DT fusion



D, T, α all composite systems with binding energies.

All we've done is re-arrange 2 p's and 3 n's.

Conservation of energy between initial and final states:

$$E_{kin,D}+m_D c^2 \ + \ E_{kin,T}+m_T c^2 \ = \ E_{kin,\alpha}+m_\alpha c^2 \ + \ E_{kin,n}+m_n c^2$$

$$m_D = m_n + m_p - m_{bind,D}$$ And similarly for T, α

$$\begin{aligned}\text{kinetic energy released} &= E_{kin,\alpha}+E_{kin,n}-E_{kin,D}-E_{kin,T}\\ &= E_{bind,\alpha}-E_{bind,D}-E_{bind,T}\\ &= 28.3-2.23-8.48\,\text{MeV}\\ &= 17.6\,\text{MeV}\end{aligned}$$

How much energy is the 17.6 MeV released in DT fusion? A lot!

Energy (Joules) in 1 kilogram of:

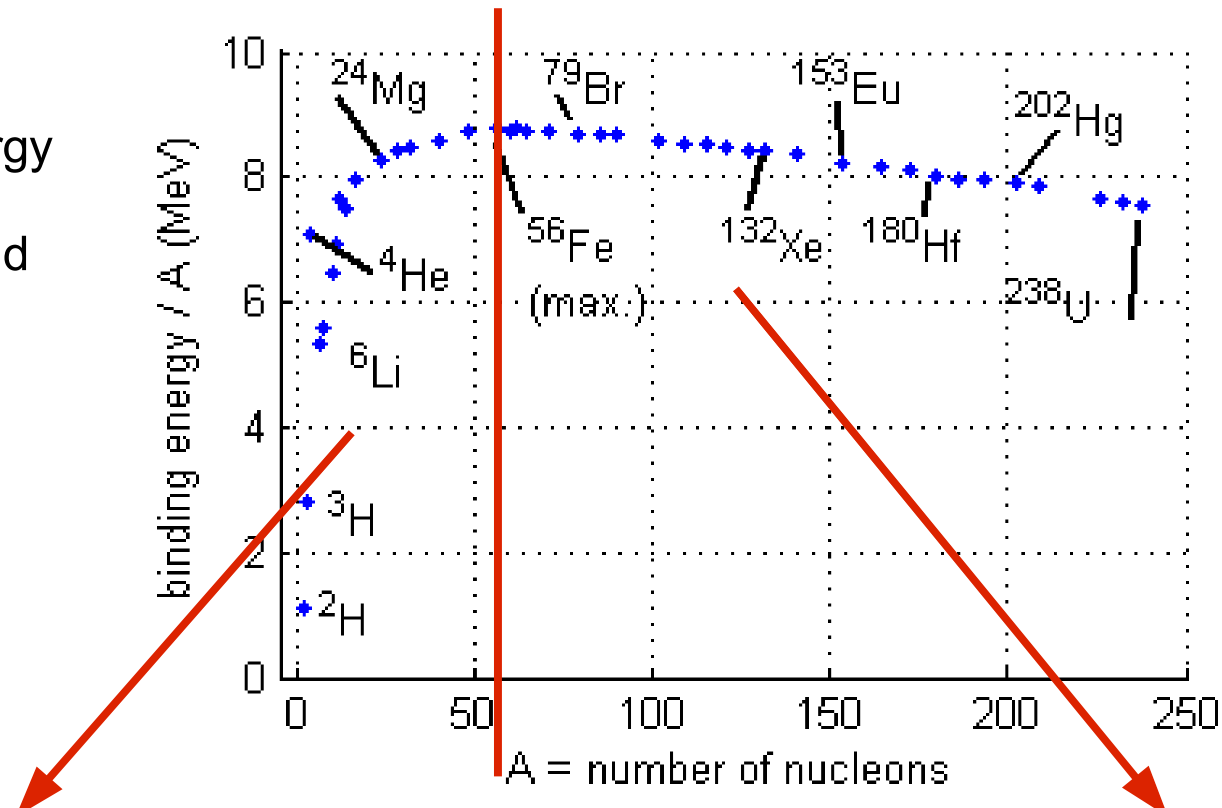
TNT (explosive)	4.2E6
Coal+air (burning)	3.3E7
Uranium 235 (fission)	2.1E12
DT (fusion)	3.4E14

1 kg of DT releases as much energy as 81 million kg, or 81 kilotons, of TNT!

Per mass, nuclear reactions are around 1 million times as energetic as chemical reactions.

Nuclear reactions release energy when final binding energy lower than initial

Binding energy per nucleon (neutrons and protons)



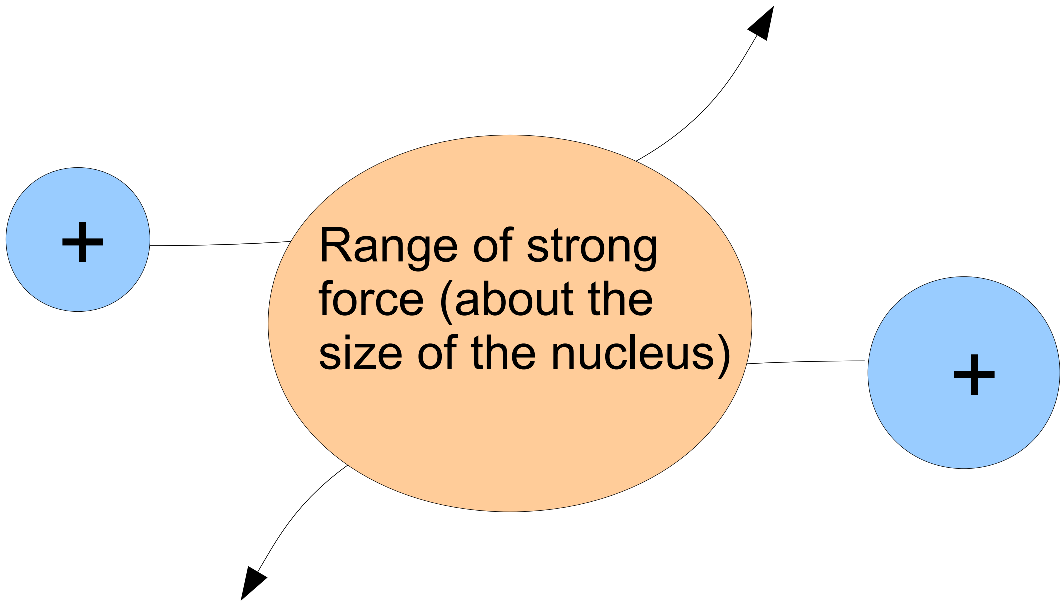
Most stable nuclei: Nickel, iron

Fusion produces energy: Light elements fuse to heavier ones

Fission produces energy: heavy element splits into lighter ones

Released energy appears as kinetic energy of reaction products: can be converted to heat when products slow down in matter.

Getting nuclei to fuse: overcoming electric repulsion



• Nuclei must have enough energy to get close enough for strong nuclear force to overcome electric repusion of protons.

• The quantum mechanical effect of “tunnelling” lets nuclei fuse even when they are several times farther away than the range of the strong force.

• Since the strong force is so short range, the nuclei must be moving very fast. In fact, they move so fast that if they were atoms with electrons bound to them, they would quickly ionize each other (knock off their electrons).

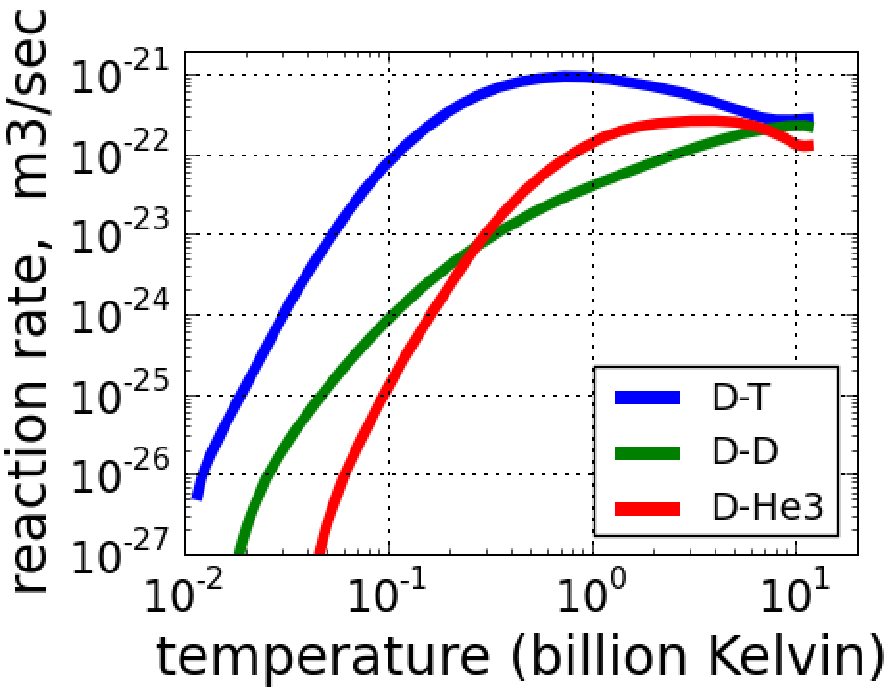
• There are no neutral atoms, but a soup of free electrons and ions. This is called a **plasma**, the so-called fourth state of matter (after solids, liquids, and gases).

Temperature needed for thermonuclear fusion

Beam fusion: acclerating a beam of nuclei into a target (stationary or another beam) is generally not an effective way to produce energy. However, this is still useful for studying the basic physics of fusion, or making sources of, e.g., neutrons.

Thermonuclear fusion: the temperature of a system (like a gas or plasma of fusion fuel) measures the *average* kinetic energy of the constituent particles. Some have more, some less, than this average. At any temperature, there will be some very fast particles that can fuse. The reaction rate can be significant even at temperature so low that most particles cannot overcome the electric repulsion.

The fast tail wags the dog!



- DT reaction happens at the lowest temperature (easier to get going).
- Atoms start ionizing at temperatures around 10,000 Kelvin, so fusion fuel will be a plasma.
- Rate falls at very high temperatures – sweet spot.

Ignition (self-sustained fusion): holy grail in fusion research

Left to itself, a plasma will expand and cool below the high temperatures needed for fusion. The electrons and ions will then recombine into atoms.

We need to stop the expansion without material walls, since plasma reacts very violently with atoms (it will start turning them into a plasma, by giving up its energy).

Besides confining the particles, we need to cofine their energy.

Energy loss: $$p_{loss} = \frac{W_{therm}}{t_E}$$

p_{loss} = rate of energy loss: conduction to boundaries, plasma expansion, radiation, …

W_{therm} = thermal energy ~ n_e T_e

n_e = electron density

T_e = electron temperature

t_E = energy confinement time

Fusion heating: p_{fus} = ~ $R[T_e]\, n_e^{\,2}$

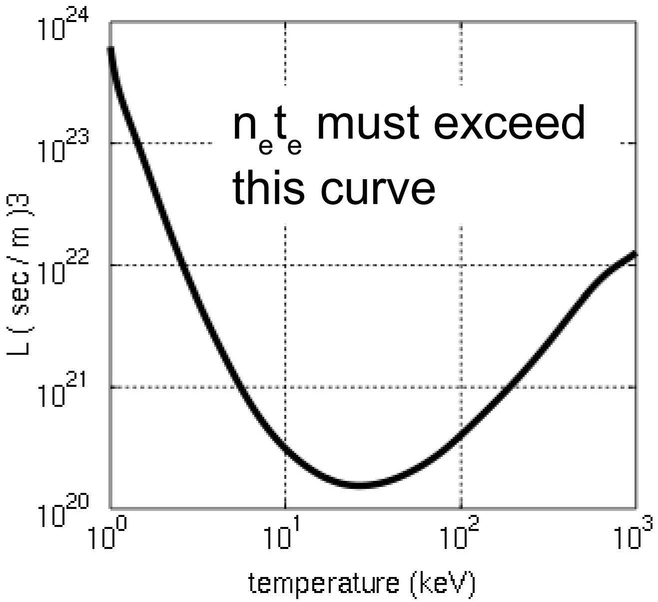
charged particles produced by fusion can heat the plasma:

Ignition condition: fusion heating exceeds energy loss. Think of a charcoal barbeque grill: if it's ignited, you don't need to add more lighter fluid or matches, but you can add a cold coal and the hot ones will heat it so it starts burning.

$$p_{fus} \geq p_{loss} \quad \rightarrow \quad R[T_e] n_e^2 \geq \frac{n_e T_e}{t_E} \quad \rightarrow \quad n_e t_E \geq \frac{T_e}{R[T_e]} = L[T_e]$$

Three key ingredients: density, temperature, confinement time

Ignition condition: $$n_e t_E \geq \frac{T_e}{R[T_e]} = L[T_e]$$



For a plasma to support substantial fusion, it must be:

- Hot: fusion reaction is appreciable only at hundreds of millions of Kelvins
- Dense: fusion reactions scale as density squared: two nuclei must find each other
- Confined: if thermal energy, or charged fusion products, escape too quickly, plasma will cool (unless external heat is added)

How the Sun does it: gravitational confinement, lots of time

- Proton-proton chain (p-pchain): 4 protons fused into helium; several steps involved.
  First step:

  proton + proton → deuteron [proton + neutron] + positron (“positive electron”) + neutrino

- P-p chain involves an inverse beta decay (requires a second proton to conserve energy):

  proton → neutron + positron + neutrino   inverse beta decay

- Beta decay is the main reason a free neutron is unstable:

  neutron → proton + electron + anti-neutrino   beta decay

- The p-p chain rate is 10^{-25} (minus 25, yes that's 25 zeros) times slower than D-T fusion at comparable temperatures. It is enormously slower because the inverse beta decay is caused by the weak nuclear force, while D-T fusion is caused by the strong nuclear force.

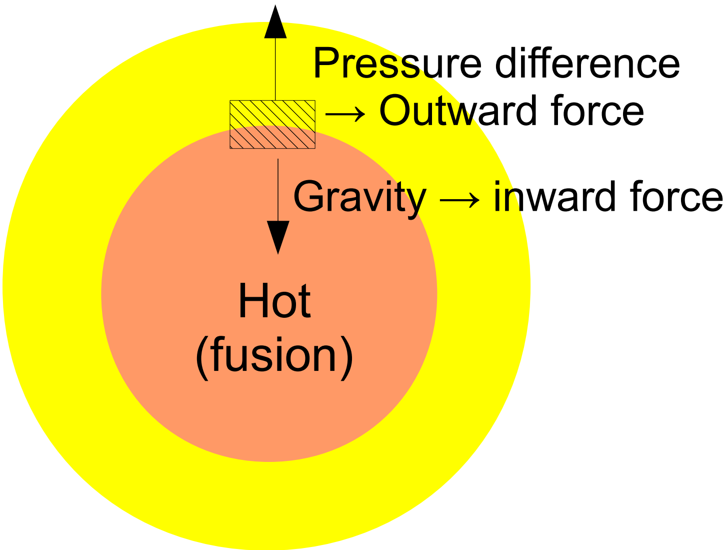
- It takes about a billion years for a typical proton in the Sun's core to undergo the p-p chain. Thus the Sun has been fusing for 5 billion years without consuming all its fuel.

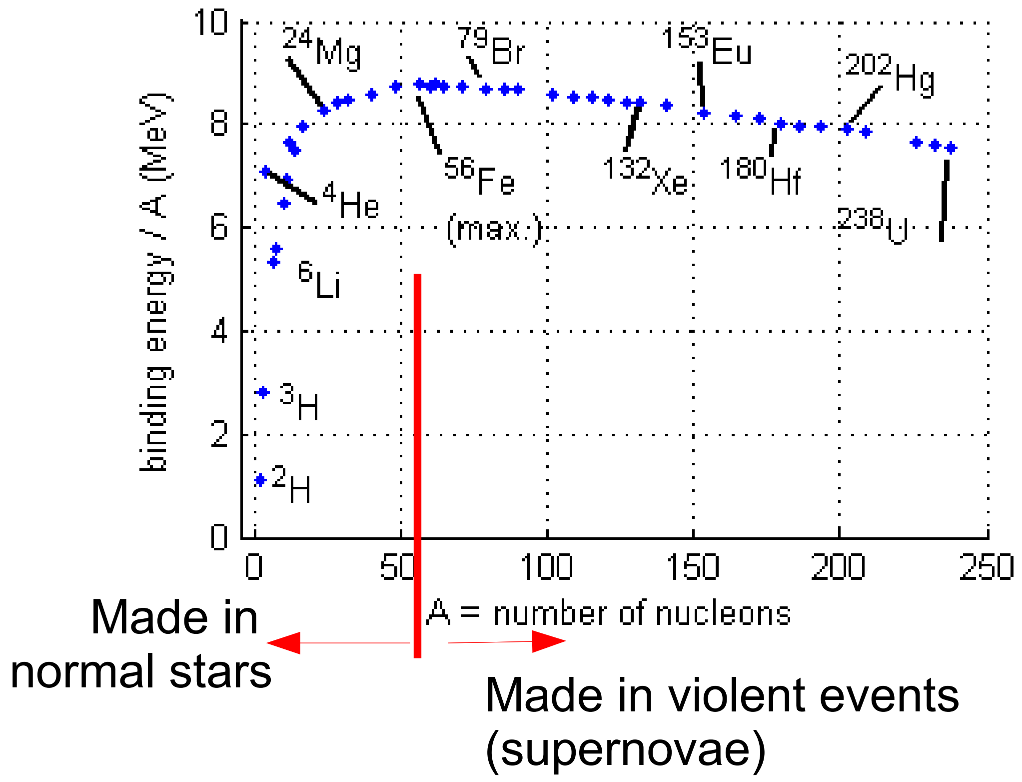
More on the Sun

•The Sun is confined by gravity, while the fusion heating in its core produces an outward pressure force that prevents gravitational collapse.

• Other fusion processes produce nuclei as heavy as nickel or iron; production of heavier elements by fusion consumes, rather than releases, energy, and is very rare in normal stellar conditions.

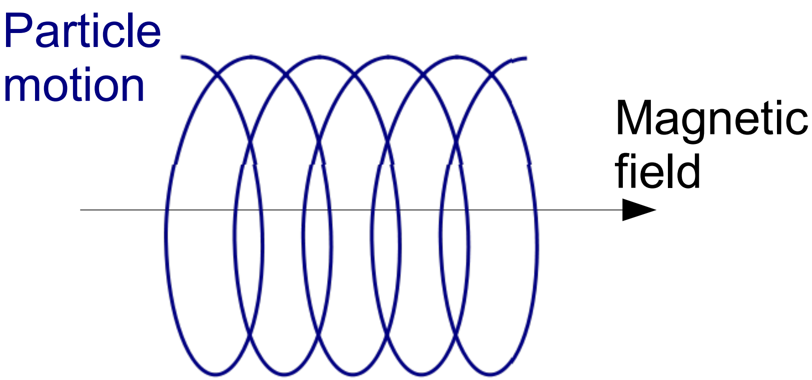
• The heavier elements are produced during violent events like supernovae.





Doing it on Earth: Magnetic confinement

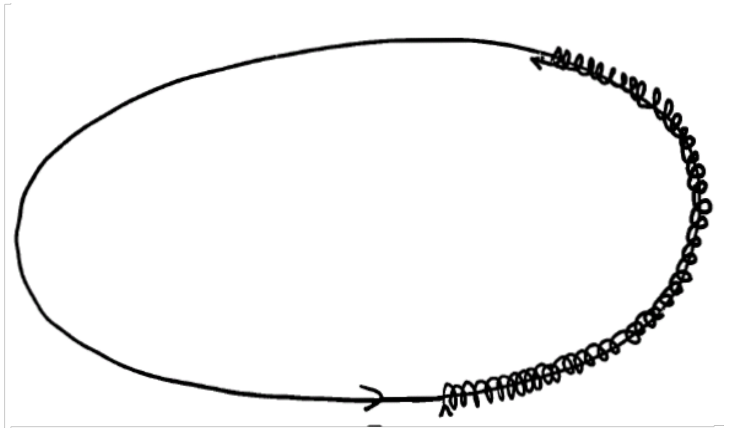
Charged particles (like electrons and nuclei) can move freely along a magnetic field, but move in circles around it.



Radius of particle orbit = “gyro-radius”
~ 1/(magnetic field)

Big field → small orbits

Closing the magnetic field on itself confines the particle orbit in all three dimensions:



There is still particle and heat transport across the magnetic field, although it is much slower than without the field.

A variety of field geometries have been explored.

The most promising so far is called the tokamak, originated by the Soviets in the 1950s.

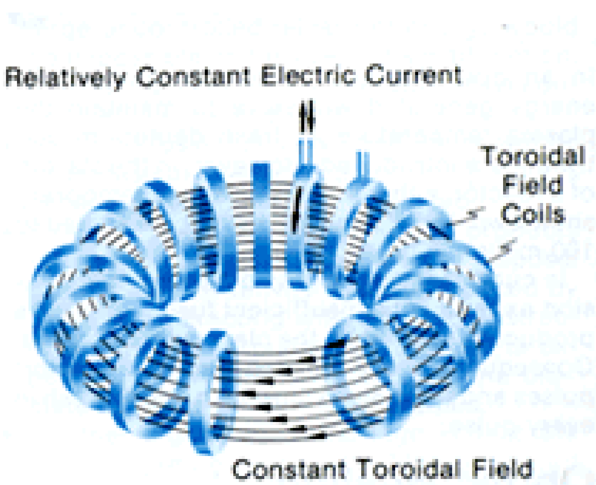
Magnetic confinement: the tokamak

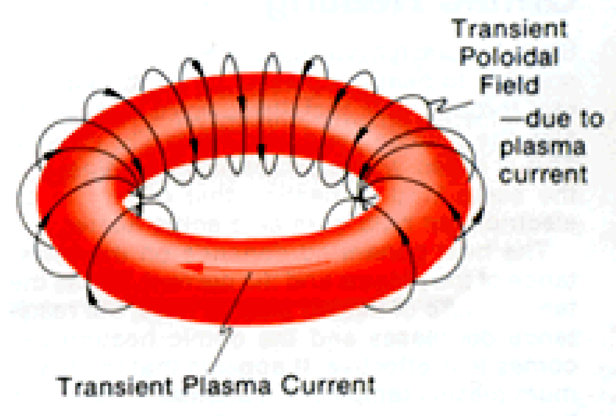
• External magnets (current-carrying coils) provide a toroidal (“the long way”) magnetic field.

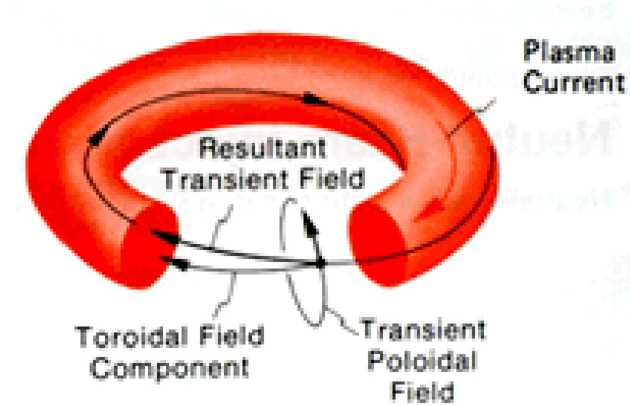
• The plasma itself carries a toroidal current, which provides a poloidal (“the short way”) field.

• This field is necessary for a tokamak plasma to be confined.

• However, it can drive instabilities that can degrade confinement.







For a power reactor, a magnetic confinement system should operate in steady state, where the heat lost is (at least mostly) balanced by heating due to fusion reactions. This is called a burning plasma.

Requires machine size to be very large compared to the radius of particle gyro-orbits.

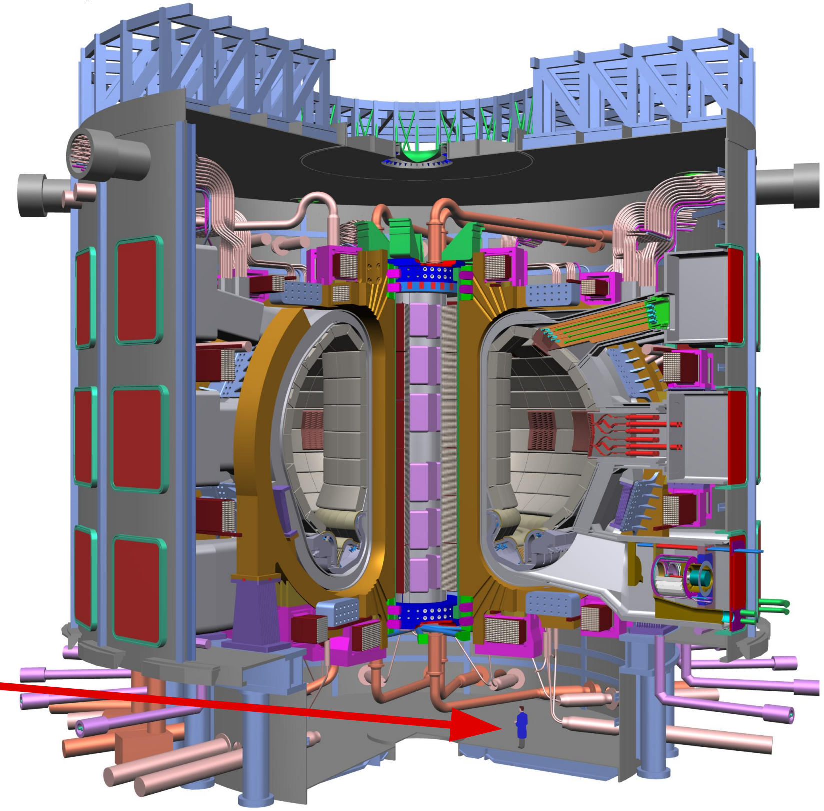
Magnetic confinement: ITER

ITER = International Experimental Thermonuclear Reactor

A tokamak experiment, which is expected to achieve a burning plasma, if not ignition, is being built in France.

Developed by an international consortium: The EU, Japan, USA, Russia, China, India, South Korea.

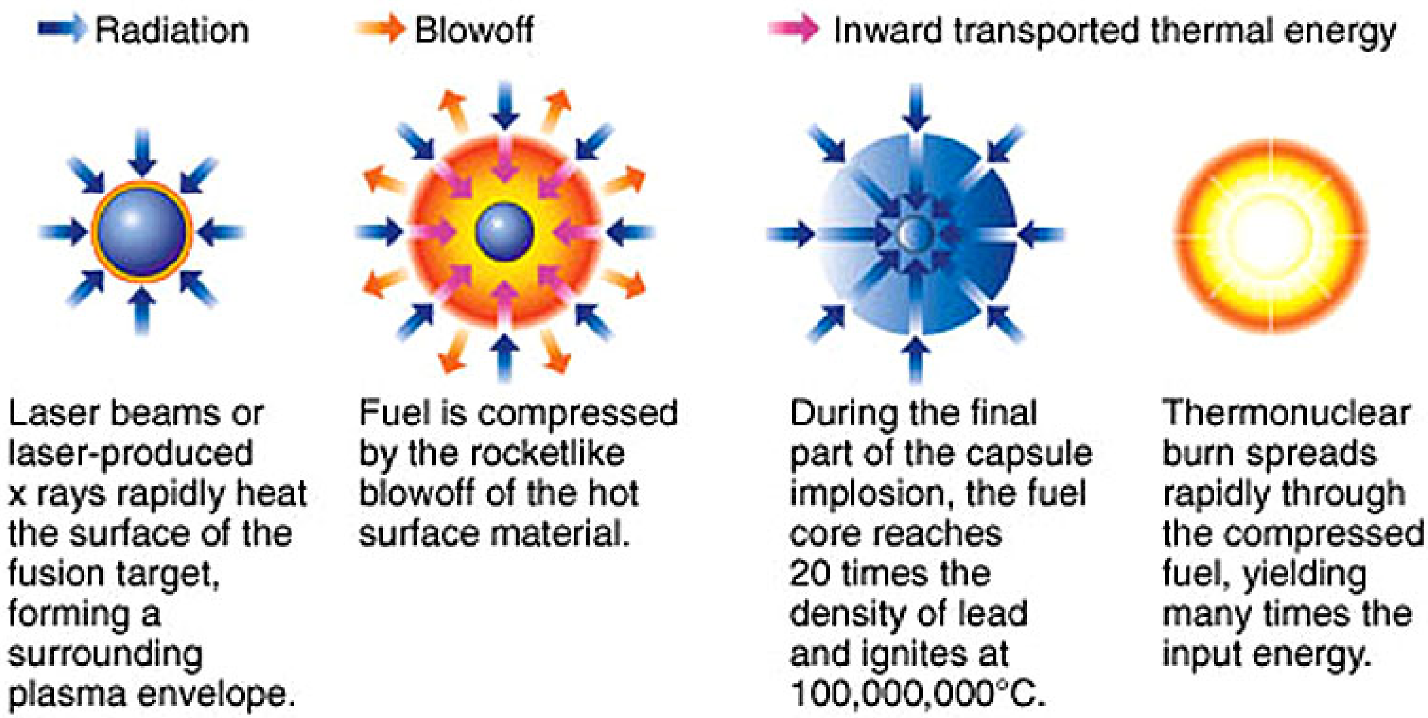
Expected to be operational ~ 2018, cost $10 billion to construct*.



For scale, there is a man

* BBC News, 17 June 2009: http://news.bbc.co.uk/2/hi/science/nature/8103557.stm

Doing it on Earth: Inertial confinement



• Use light to boil off matter from a spherical pellet of fusion fuel. This ablation process causes the blowoff to expand, and the pellet to implode inward. Like a spherical rocket.

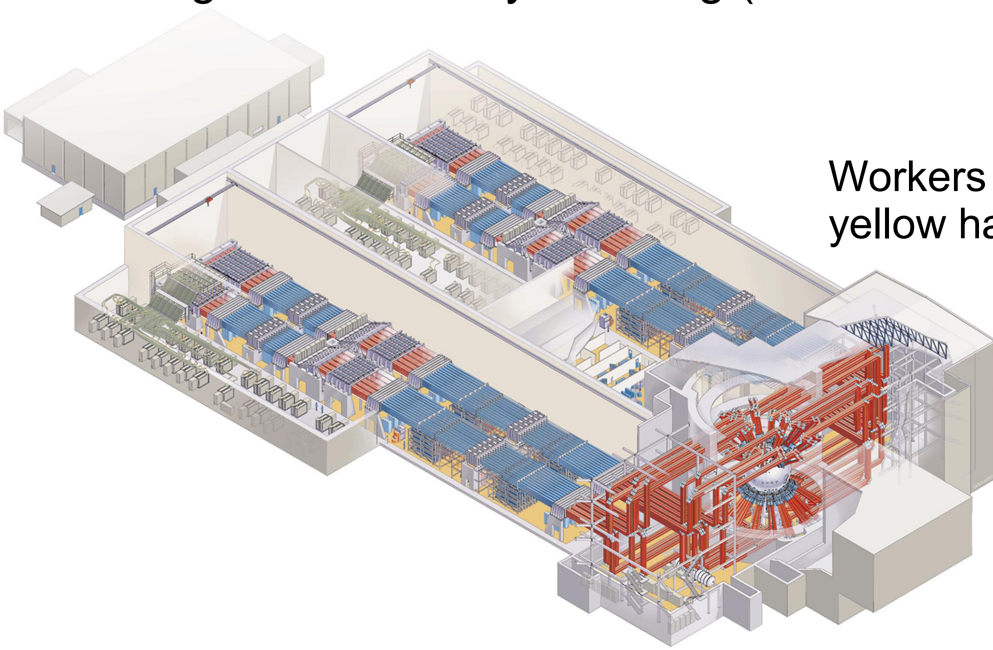
• The compressed fuel will hopefully reach high enough densities (hundreds of times that of liquids) and temperatures for fusion to start.

• What's confining the fuel? Nothing! The compressed fuel disassembles very rapidly, but not instantly, since it has mass (inertia).

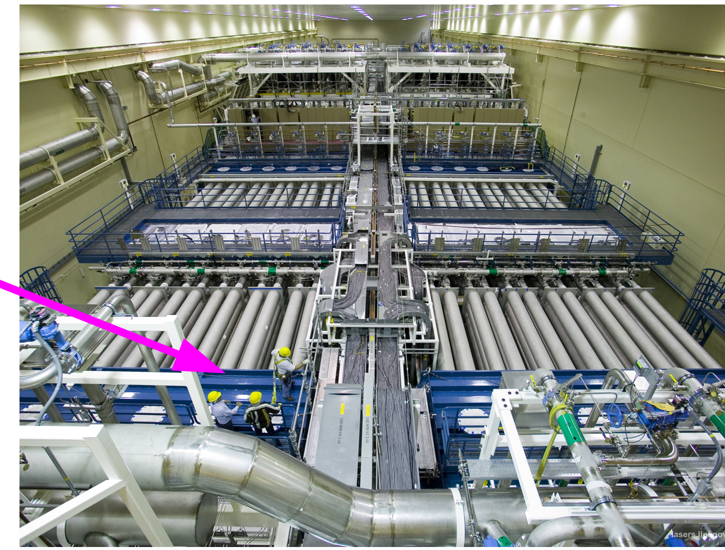
• If done right, fusion will occur before dissassembly.

Inertial confinement fusion: LLNL's National Ignition Facility (NIF)

NIF building is about 300 yards long (3 football fields), most of which is laser components.

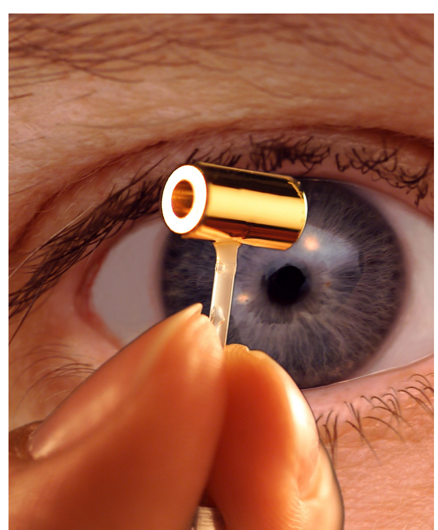


Workers w/
yellow hardhats

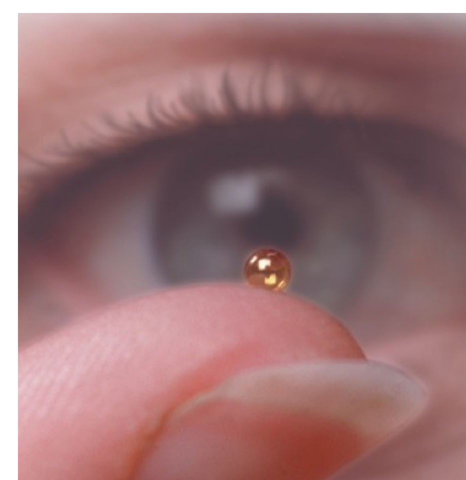


1.5 megajoules (360 Calories) of laser energy is deposited, over several nanoseconds, into:

A hollow gold cylinder (hohlraum), which gets hot and radiates x-rays



The x-rays drive the ablative implosion of a fuel capsule inside the hohlraum



More on the National Ignition Facility (NIF)

• Biggest (most energetic, largest building, most expensive) laser in the world.

• Biggest experiment at LLNL.

•Construction started ~1995; cost ~ $4 billion, about twice as original budget; cost overruns developed in the late 1990s, causing political problems.

• NIF is the culmination of earlier, smaller laser systems at LLNL and elsewhere.

• NIF is being funded for stewardship of the US nuclear stockpile, although energy and basic science (e.g. astrophysics) have always been secondary goals.

• Unlike magnetic fusion, ICF has a military “customer.” That's magnetic fusion's real problem!

• Also unlike magnetic confinement, ICF is inherently pulsed and not steady state: once all the fuel in a capsule is burnt up, that's it, you need another capsule and another laser pulse.

• For energy production, the NIF lasers are tremendously inefficient and way too low a repetition rate.

• Replacement “drivers” are possible: diode-pumped lasers, beams of heavy ions, wire-array “Z pinches.”

Uses of fusion: boiling water to make electricity

- “Fission (or fusion) is just another way to boil water.”

- The energetic fusion products will be slowed down in a blanket surrounding the fusion source. This heat will then be exchanged with a water boiler, which will drive a steam turbine.

- Electricity generation by fossil fuels, fission, or fusion all rely on steam turbines and boiling water.

- All fusion approaches that look promising are “big:” can't really be tested, and not productively used, on a small scale.

- You can't power a calculator off fusion, you have to start with a power plant. This has impeded fusion development, funding, and investment. But no one's thought of a “Mr. Fusion” a la Back to the Future.

Fusion Development: Nuclei for Peace?

Oft-heard quips: “Fusion has been 30 years away for the last 60 years.”
“Fusion is the future of energy, and always will be.”

Money, not time, is the correct variable to plot fusion progress against. Fusion is ~ $100 billion problem.

Given that money, no constraints, we could make a reactor in 10 years.
- Still couldn't be done overnight: serious scientific challenges remain.

Per year, in trillions of dollars:
World GDP: 55 Energy market: 3 Energy R&D: 0.012 US pet food*: 0.014

Magnetic fusion: limited by lack of funding – definite plan for experiment to test reactor physics (ITER), but won't be online til ~2020.

Inertial fusion: NIF is working toward ignition in the next few (not 60) years, but to make a power plant several miracles needed:
- Much more efficient laser (or replacement)
- Fabricate fuel pellets for < $0.25, and make ~ 1 million per day
- Ignite 10 pellets *a second* to get about a 1000 megawatts electric.

*Source: World Bank

More Fusion Development

Besides developing a fusion system, a lot of research is needed on materials for a working reactor. The output of a fusion system, especially the energetic neutrons, is much more intense and damaging than in a fission reactor.

The IFMIF (International Fusion Material Integration Facility) had been proposed to address the matierals issues. Comparable in budget to NIF or ITER. No one has been willing to fund it yet.

Fusion's attractive features:

- Inexhaustible (millions of years) of fuel on Earth
- No atmospheric pollution

But fusion is not a silver bullet:

- It will not be free – like nuclear fission, it will have large capital costs
- The cost of electricity will probably be a few times that of coal today

Fusion shares some problems with fission, but in much reduced form:

Radioactive waste: fusion neutrons will cause the reactor materials to become radioactive, but the half-lives will be 10-100 years, not the 10,000 of some fission waste

Nuclear proliferation: you can't build a bomb out of a fusion reactors (there is no uranium or plutonium), but fusion neutrons can be used to breed plutonium from uranium.

Best (or worst) of both worlds: fission-fusion hydrid:
Use fusion neutrons to breed fission fuel, and/or burn up fission waste into benign material

Summary: what fusion is and where we stand

• Nucler fusion, and fission, release kinetic energy by increasing the nuclear binding energy of the final products compared to the initial “fuel” nuclei.

• Nuclear reactions release millions of times as much energy per fuel mass as chemical reactions – thus an atomic bomb with 10 kg of plutonium can produce as much energy as 10 kilotons (10 million kg) of TNT explosives.

• Fusion requires enormous temperatures (~100 million degrees), high enough fuel density, and long enough confinement time.

• Magnetic fusion: use magnetic fields to roll up particle orbits. ITER machine being build in France, should be done around 2018.

• Inertial fusion: National Ignition Facility (NIF), at Lawrence Livermore National Lab, is starting experiments now.

• Long-term proposition: fusion is going to take time and more importantly money to develop. It is too far off for private companies to invest in, so we need public research funding.

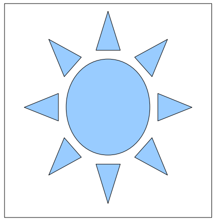
• Write your Congresspeople!

Backup Slides

More on energy

Work: To do work on a massive particle means to change its energy.

Energy is conserved: the *total* amount of it doesn't change.
It is conserved locally: total energy in a region of space only changes due to imports / exports.
Like flowing liquids: amount of water in a bucket only changes if water poured in from elsewhere.



Energy in the box can change forms, but total can only change if substances enter or leave box.

Substances without mass (sometimes called **fields**) also possess energy.
Includes light, electric and magnetic fields, gravity.

Potential energy: related to energy in fields. Frequently used in physics (they may not tell you in high school that it is field energy!). Very useful concept in solving physics problems.

Example: particles with electrical charge exert forces, and do work, on each other. They do this by generating an electric field, which contains energy. This is treated as potential energy.

Forms of energy (loosely speaking): heat, mechanical, electrical, chemical, nuclear, sound, flow energy (kinetic energy of flowing fluids, like wind or water waves).

Units of energy (all measuring the same thing): Joules (the official metric unit), ergs, British thermal units (BTUs), (kilo-)calories, Kelvins, electron-Volts, kilotons of TNT, ...

Power: rate of chance of energy. Units: 1 Watt = 1 Joule / second.

Kilowatt-hour: Convenient energy unit for household use: the energy obtained by doing work at a rate of one kilowatt, for one hour of time.