

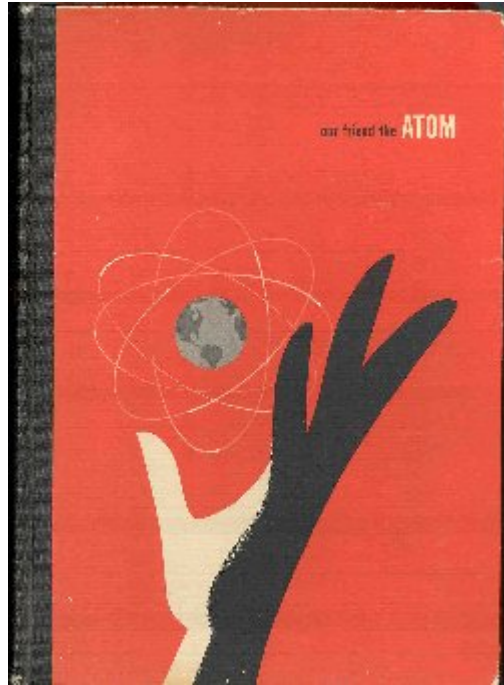
Fusion: Our Friend the Nucleus

David J. Strozzi

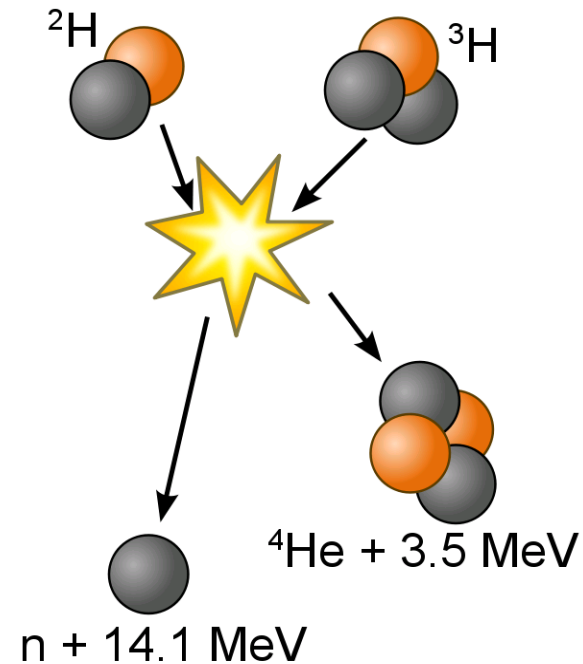
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Our Friend the Atom: Disney film (1957)



Deuterium-tritium fusion

Internet resources:

Wikipedia (of course)

www.pppl.gov

hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html

fire.pppl.gov

lasers.llnl.gov

fusedweb.llnl.gov

www.iter.org

Splash Fall 2009
Stanford Univ.

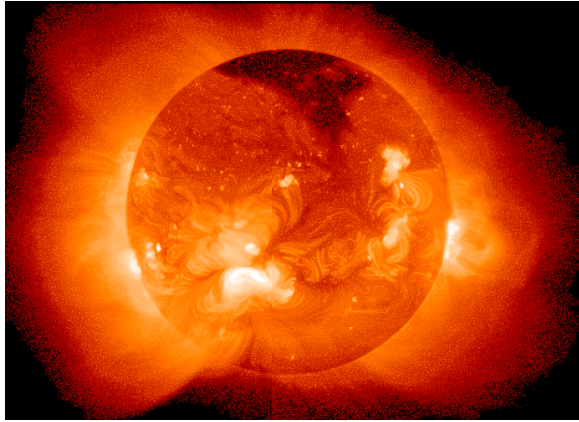
Our Friend the Nucleus

David J. Strozzi

Points of this class

- Expose you to some basic ideas about fusion and nuclear physics, as well as applications.
- Think about some basic physical concepts, motivated by fusion.
- You (probably) don't know any “real” physics, which takes a long time to learn.
- We will of course do very simplified things, but we will stay faithful to the truth.
- This class is a chance to think seriously for a few hours, which is one of the main values of learning science and math - even if you're never going to use the subject content.
- You get to talk to each other and a real live scientist: yes you can sit in front of a computer and surf the web or wikipedia, but now you get to interact with actual humans!
- Spark some interest in science.
- Convince you (or your parents) to spend tax money on science.....
- Ask a lot of questions!

Nuclear Menu



The Sun – very slow fusion



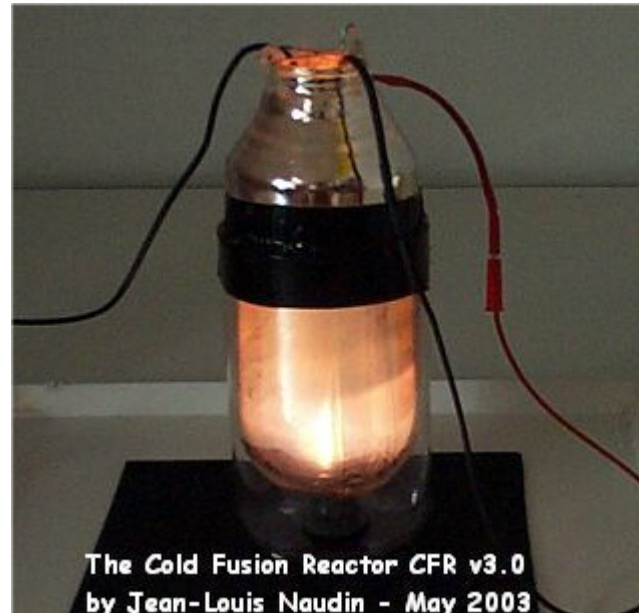
Fission power –
it works today



National Ignition Facility (LLNL)
inertial fusion



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



Cold fusion?



Tokamak – magnetic fusion

Class Outline

Basics (first class)

1. Energy, and how nuclear reactions (fission and fusion) “produce” it
2. Fusion reactions – deuterium-tritium, proton-proton
3. Achieving nuclear fusion – overcoming nuclear electric repulsion

Applications (second class)

1. Stars – what they fuse, how they function, how elements are made
2. Nuclear explosives
3. Fusion energy schemes – magnetic confinement and inertial confinement

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: $E_{\text{nat}} = E_{\text{mass}} + E_{\text{kin}}$

Mass energy: $E_{\text{mass}} = m * c^2$

Kinetic energy: $E_{\text{kin}} = (\gamma - 1) m * c^2$
 $\approx (\frac{1}{2}) m * v^2$

thus saith Einstein! More later

$\gamma = [1 - v^2/c^2]^{-1/2}$ v = particle speed c = speed of light
 Newtonian physics; (speed v much less than c)

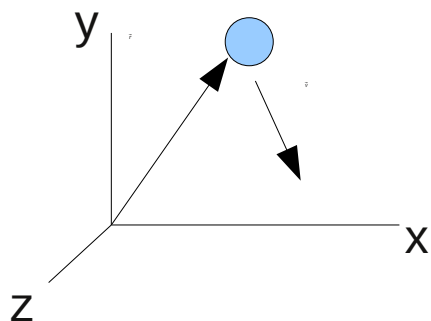
Fields: gravity, electric and magnetic (e.g., light): generally massless, but possess energy, called field energy.

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

acceleration: $\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$

Force: $\vec{F} = m \vec{a}$ m = mass

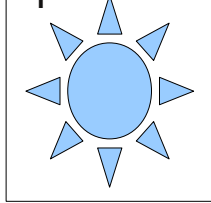
More on energy

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 change 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.

Richard Feynman on Energy

I want you to imagine that a mother has a child whom she leaves alone in a room with 28 absolutely indestructible blocks. The child plays with the blocks all day, and when the mother comes back she discovers that there are indeed 28 blocks; she checks all the time the conservation of blocks! This goes on for a few days, and then one day when she comes in there are only 27 blocks. However, she finds one block lying outside the window ... Suppose one day when the mother comes to count the blocks she finds that there are only 25 blocks, but suspects that the child has hidden the other three blocks in a little toy box. So she says, 'I am going to open the box.' 'No', he says, 'you cannot open the box.' Being a very clever mother she would say, "I know that when the box is empty it weighs 16 ounces, and each block weighs 3 ounces, so what I am going to do is to weigh the box'. ...

Now I would like to draw my analogy, and tell you what is common between this and the conservation of energy, and what is different. First suppose that in all of the situations you never saw any blocks. ... The mother would always be calculating a whole lot of terms like 'blocks in the box', 'blocks in the [sink] water', and so on. With energy there is this difference, that there are no blocks, as far as we can tell. ...

What we have discovered about energy is that we have a scheme with a sequence of rules. From each different set of rules we can calculate a number for each different kind of energy. When we add all the numbers together, from all the different forms of energy, it always gives the same total. But as far as we know there are no real units, no little ball-bearings. It is abstract, purely mathematical, that there is a number such that whenever you calculate it it does not change. I cannot interpret it any better than that.

-Richard Feynman, The Character of Physical Law, section 3.

Richard Feynman* on Physicists

Physicists sometimes feel so superior and smart that other people would like to catch them out once on something. I will give you something to get them on. They should be utterly ashamed of the way they take energy and measure it in a host of different ways, with different names. It is absurd that energy can be measured in calories, in ergs, in electron volts, in foot pounds, in BTUs, in horsepower hours, in kilowatt hours – all measuring exactly the same thing. For those who want some proof that physicists are human, the proof is in the idiocy of all the different units which they use for measuring energy.

-Richard Feynman, The Character of Physical Law, section 3

* recipient of 1965 Nobel prize in physics, *after* he had accomplished something.

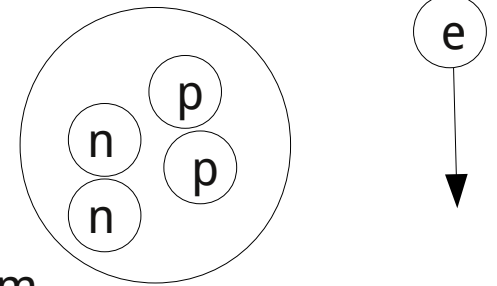
The four forces, atoms and nuclei

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 attract.
- 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 unit 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 its parts?

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

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

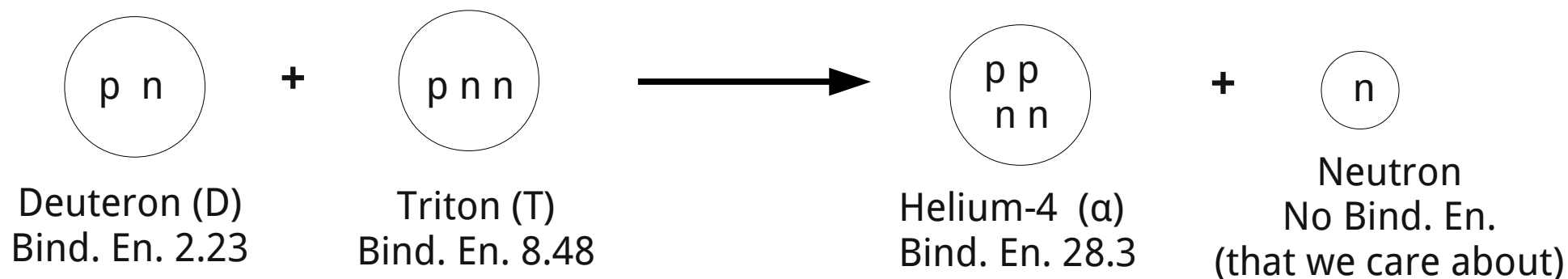
$$m_{sys} = \sum_i m_i - m_{bind}$$

$$m_{bind} c^2 = E_{bind} = - \sum_i E_{kin,i} - E_{pot} \quad \text{"binding energy" or "mass defect"}$$

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 ($m \cdot c^2$).

DT fusion: a VIP (very important process)



Deuteron = deuterium nucleus; stable; naturally occurring (1/6500 of terrestrial hydrogen)
"heavy water" = D₂O

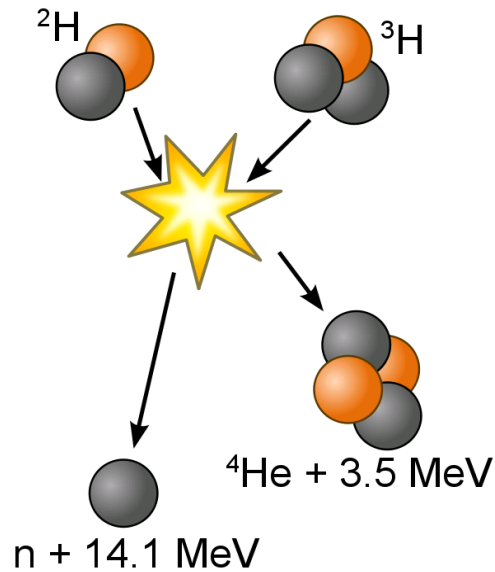
Triton = tritium nucleus; unstable (half-life of 12.3 years); trace amounts on Earth;
Can be produced from lithium: $\text{Li6 (3p, 3n) + n} \rightarrow \alpha + \text{T}$

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:

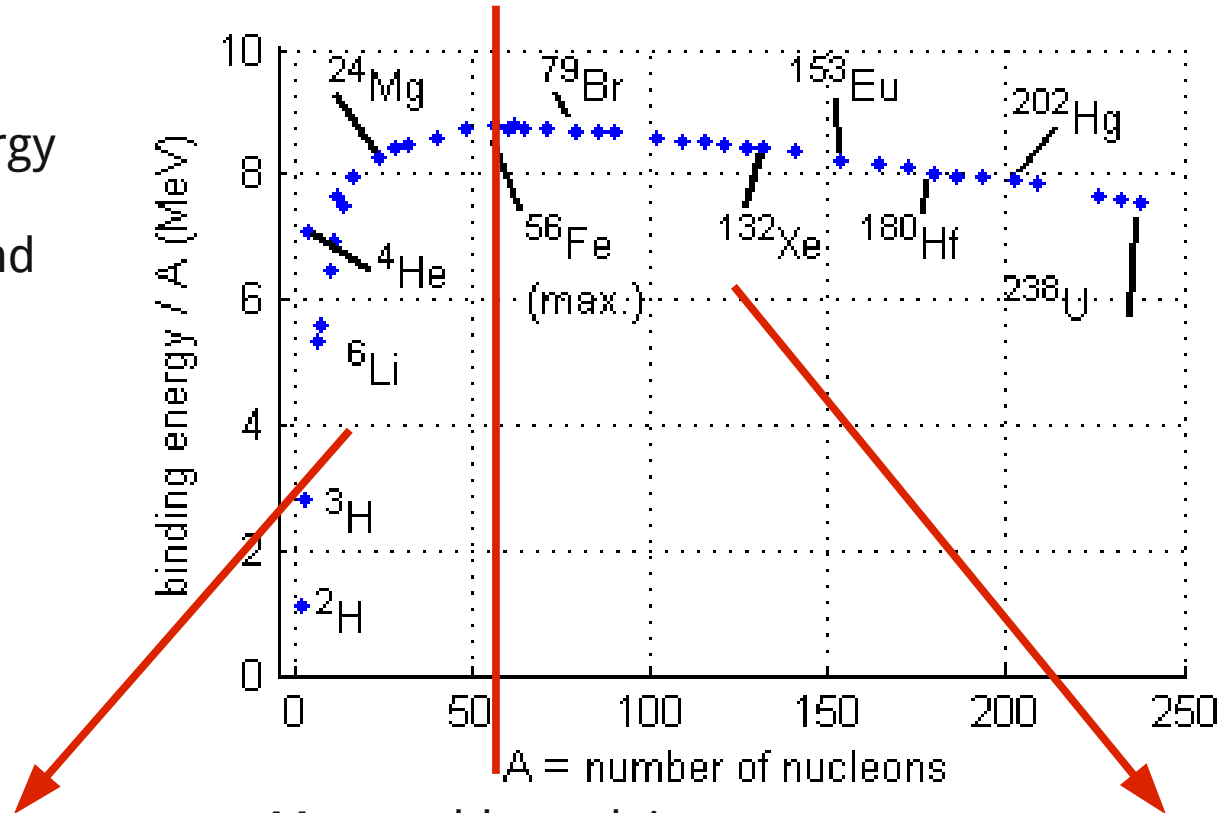
TNT (explosive)	4.2E6
Coal+air (burning)	3.3E7
Uranium 235 (fission)	2.1E12
DT (fusion)	3.4E14

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)



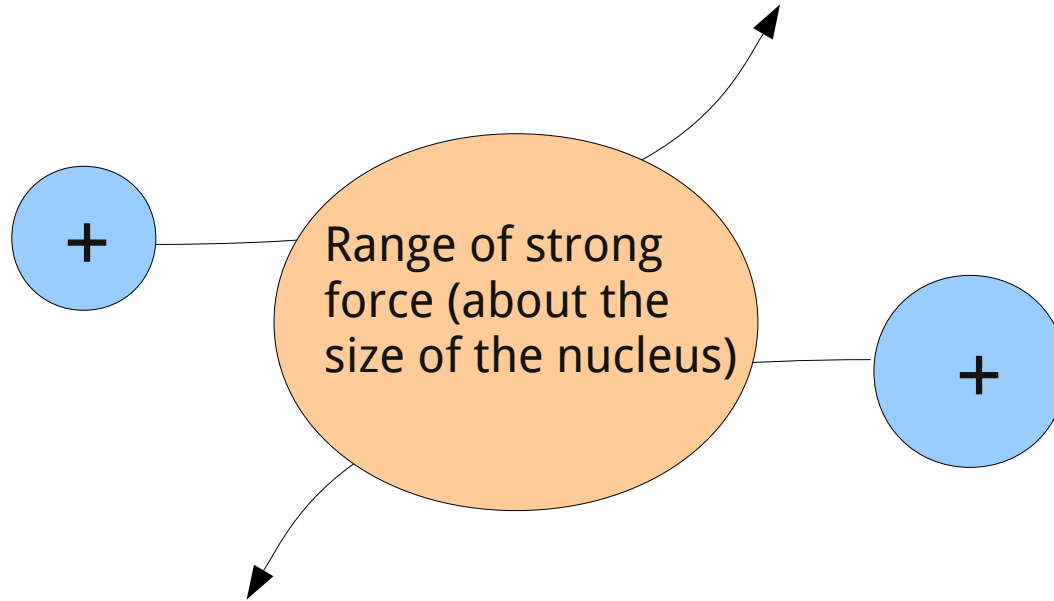
Fusion produces energy:
Light elements fuse to heavier ones

Most stable nuclei:
Nickel, iron

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



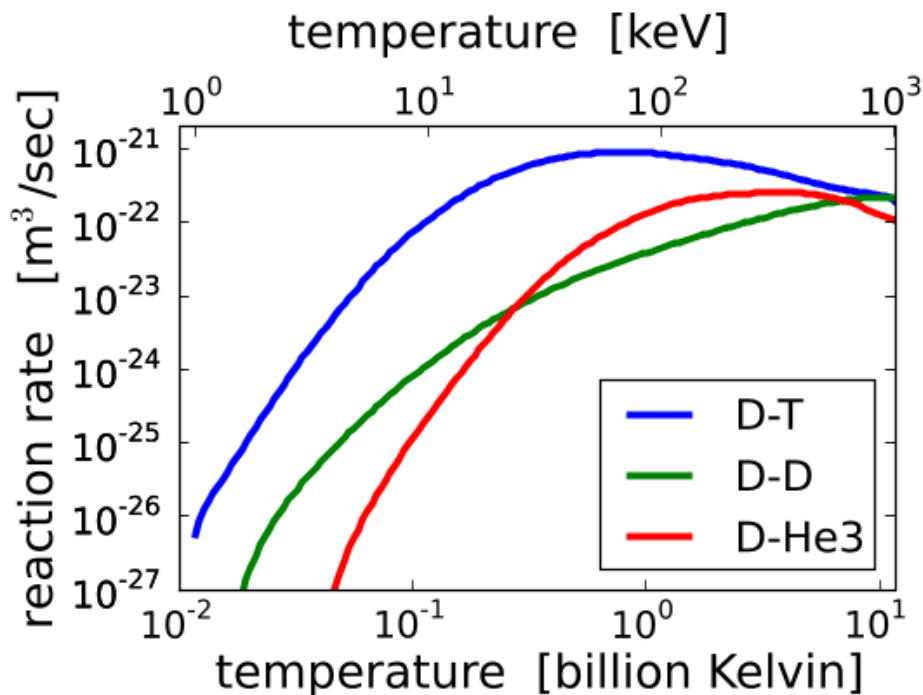
- Nuclei must have enough energy to get close enough for strong nuclear force to overcome electric repulsion of protons.
- The quantum mechanical effect of “tunnelling” lets nuclei fuse even when they are several times farther away than the range of the strong force.
- Since the strong force is so short 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: accelerating 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 confine their energy.

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

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

Fusion heating: $p_{fus} = \sim R[T_e] n_e^2$
charged particles produced
by fusion can heat the plasma:

W_{therm} = thermal energy $\sim n_e T_e$

n_e = electron density

T_e = electron temperature

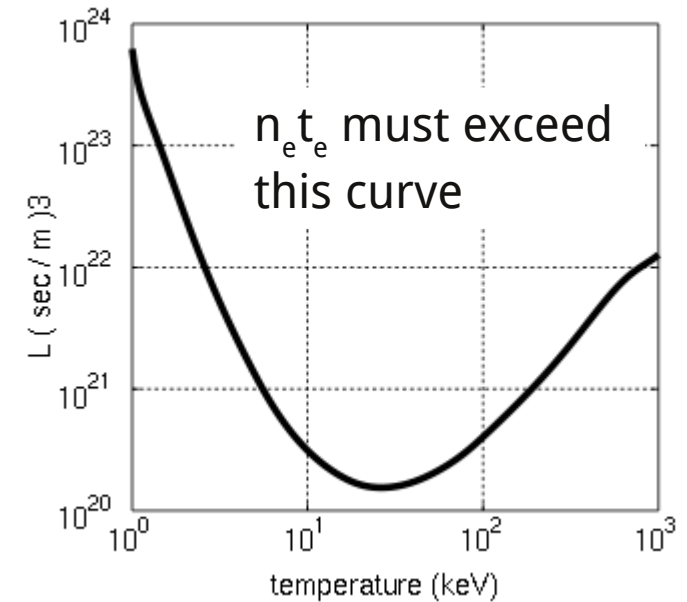
t_E = energy confinement time

Ignition condition: fusion heating exceeds energy loss. Think of a charcoal barbecue 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 \rightarrow deuteron [proton + neutron] + positron (“positive electron”) + neutrino

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

proton \rightarrow neutron + positron + neutrino inverse beta decay

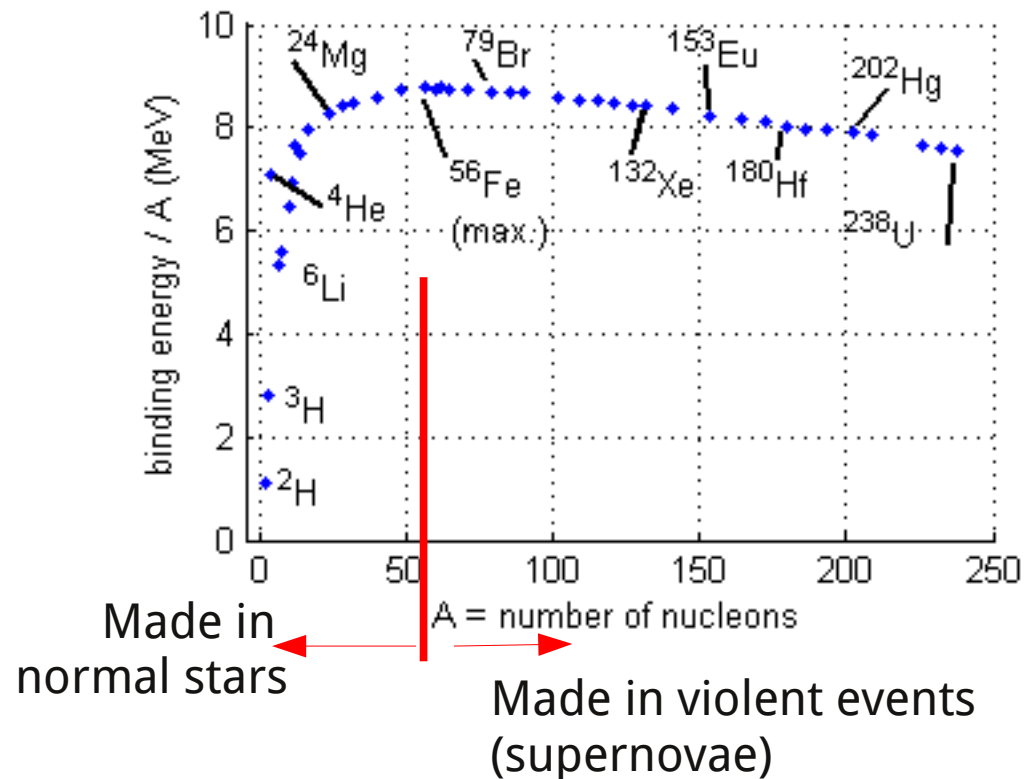
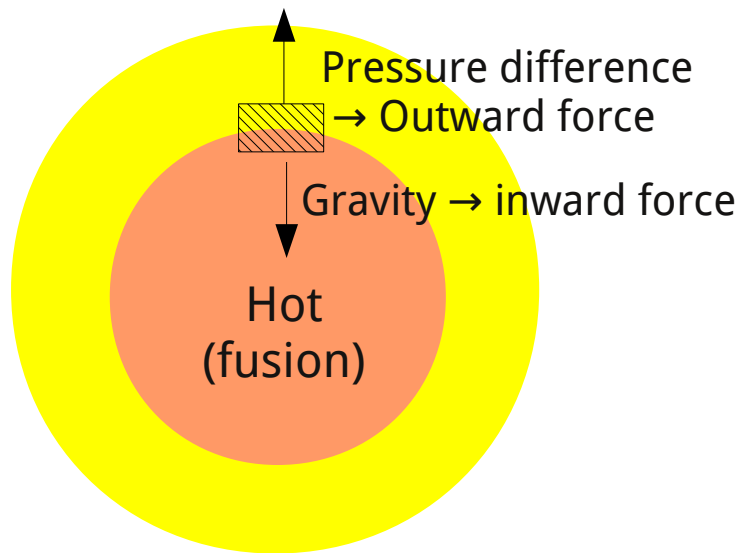
- Beta decay is the main reason a free neutron is unstable:

neutron \rightarrow proton + electron + anti-neutrino beta decay

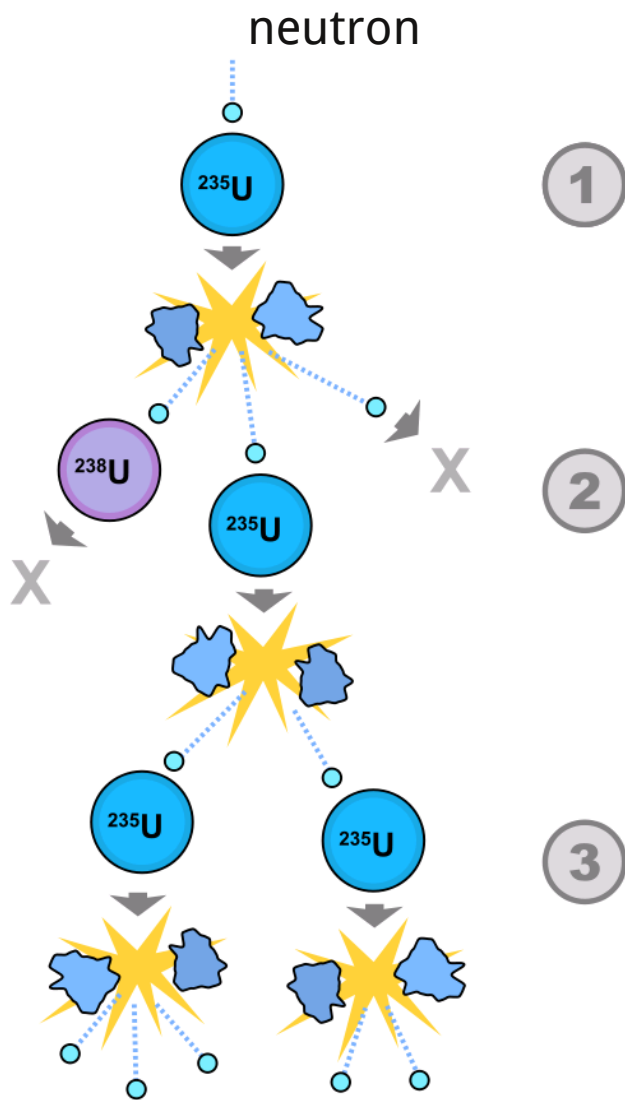
- The p-p chain rate is 10^{-25} (minus 25, yes that's 25 zeros) times slower than D-T fusion at comparable temperatures. It is enormously slower because the inverse beta decay is caused by the weak nuclear force, while D-T fusion is caused by the strong nuclear force.
- It takes about a billion years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



Nuclear fission: the bigger they are the harder they fall



Fission: splitting of a nucleus into smaller fragments.

A nucleus is **fissile** if a “slow” neutron can cause it to fission, and this fissioning produces neutrons which can lead to subsequent fissions.

This allows for a **chain reaction**.

Very few isotopes are fissile. Uranium (U)-235 and Plutonium (Pu)-239 are two such.

Natural Uranium is 99.28% 238 isotope, 0.7% 235.

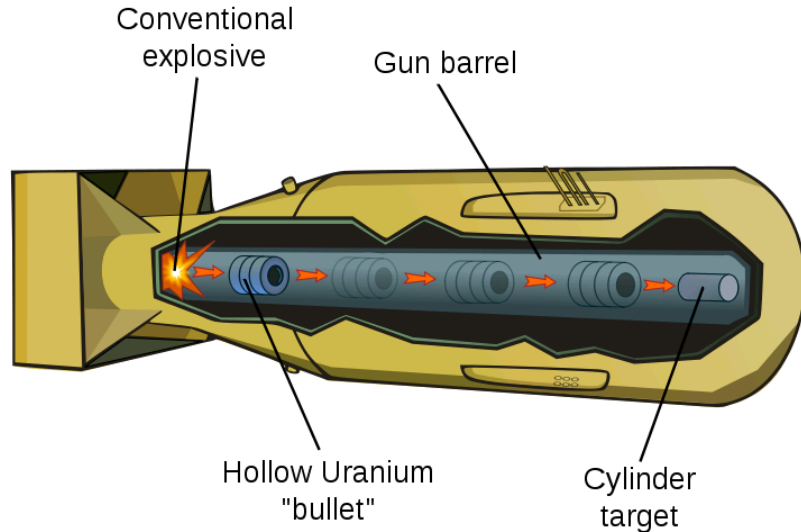
U-238 is not fissile, although it does decay radioactively, half-life of 4.5 billion years. When hit by a neutron it becomes Pu-239, which is fissile.

Depleted Uranium is more purely U-238 than naturally occurring, i.e., the leftover from enrichment.

Nuclear Explosives (or, how I learned to stop worrying and love the bomb)

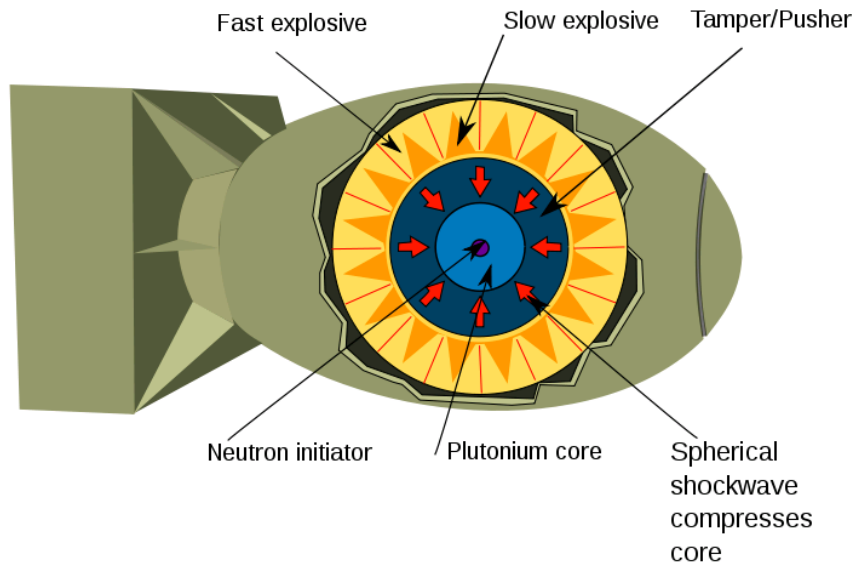
Gun assembly: Hiroshima

Little Boy, U-235, ~15 kT (kiloton) yield



Implosion assembly: Nagasaki

Fat Man, Pu-239, ~20 kT yield



Hydrogen bombs (thermonuclears):

Two stages (Teller-Ulam design): radiation from fission stage implodes a second fusion stage.

First US test: Ivy Mike, 1952, cryogenic D-T.

Not a usable weapon: huge device to keep DT cold. Yield ~10 MT (million tons).

First USSR test of "layer cake" design (not two-stage): 1953, Lithium-deuteride. Tritium bred in-place, small enough to be a weapon, but much smaller yield ~400 kT.

Putting it together: 1954 Castle Bravo US test: 15 MT yield, Li-D fuel and two-stage. Pacific islanders and Japanese fishing boat crew exposed to fallout, some died. Yield was 2.5 times expected, since Lithium-7 + neutron fusion not accounted for. Thanks, Los Alamos!

Before we get carried away...

Our tragedy today is a general and universal physical fear so long sustained by now that we can even bear it. There are no longer problems of the spirit. There is only the question: When will I be blown up? Because of this, the young man or woman writing today has forgotten the problems of the human heart in conflict with itself which alone can make good writing because only that is worth writing about, worth the agony and the sweat.

-William Faulkner, banquet speech, Nobel prize in literature, 1949

I see the danger not in the number or quality of the weapons or in the intentions of those who hold them but in the very existence of weapons of this nature, regardless of whose hands they are in. I believe that unless we consent to recognize that the nuclear weapons we hold in our hands are as much a danger to us as those that repose in the hands of our supposed adversaries there will be no escape from the confusions and dilemmas to which such weapons have brought us, and must bring us increasingly as time goes on. For this reason, I see no solution to the problem other than the complete elimination of these and all other weapons of mass destruction from the national arsenals; and the sooner we move toward that solution, and the greater courage we show in doing so, the safer we will be.

- George F. Kennan, architect of US Cold-War containment policy, *New Yorker*, Nov. 2 1981

Even if we get rid of nuclear bombs, we'll always have knowledge of their workings.

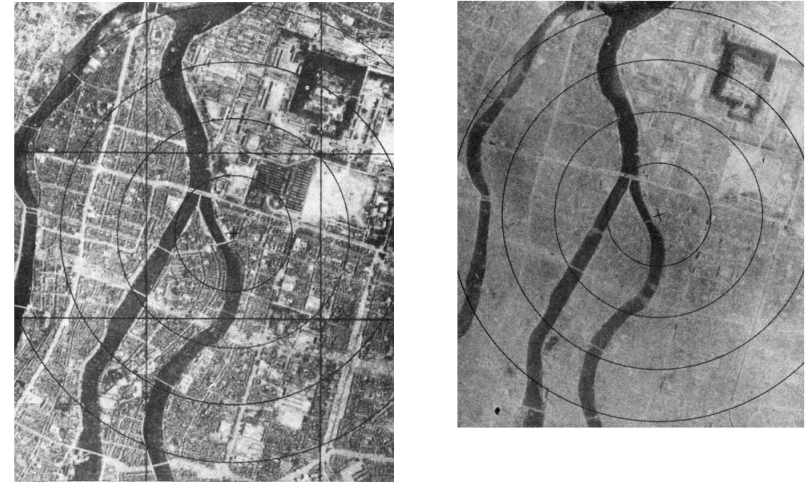
- David J. Strozzi, winner of nothing

Before we get carried away...

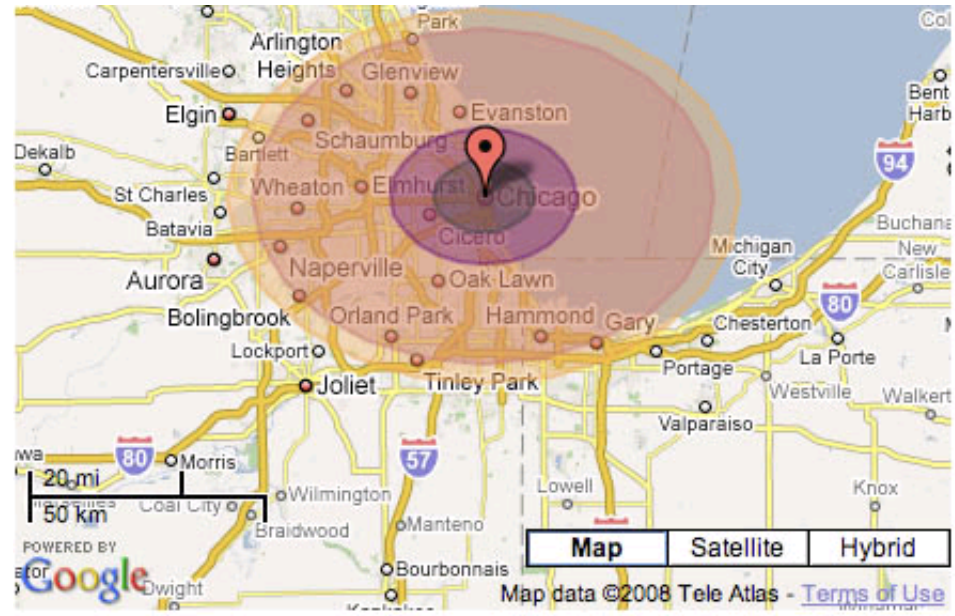
Nagasaki after



Hiroshima before and after



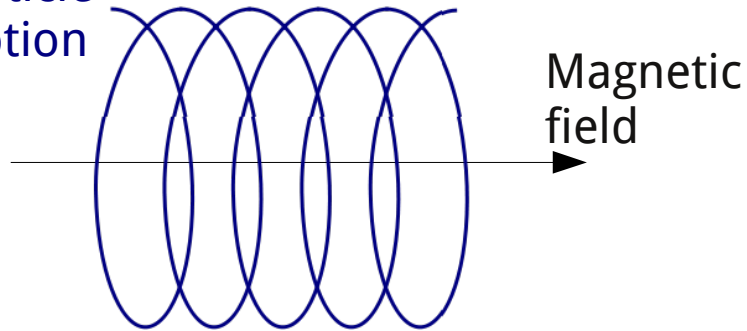
If Tsar Bomba were dropped on Chicago:



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.

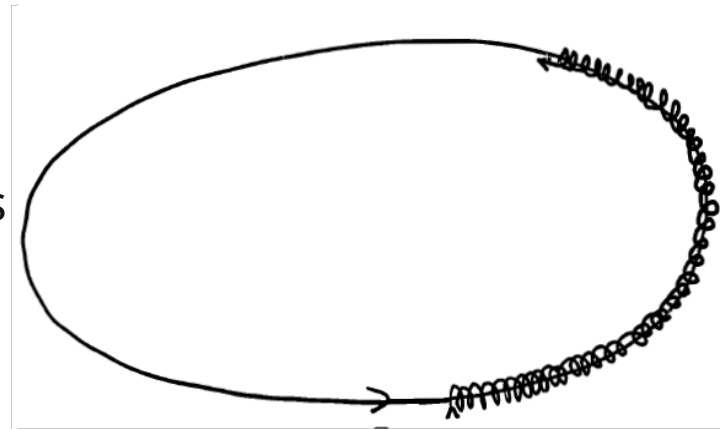
Particle motion



Radius of particle orbit = "gyro-radius"
 $\sim 1/(\text{magnetic field})$

Big field \rightarrow small orbits

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



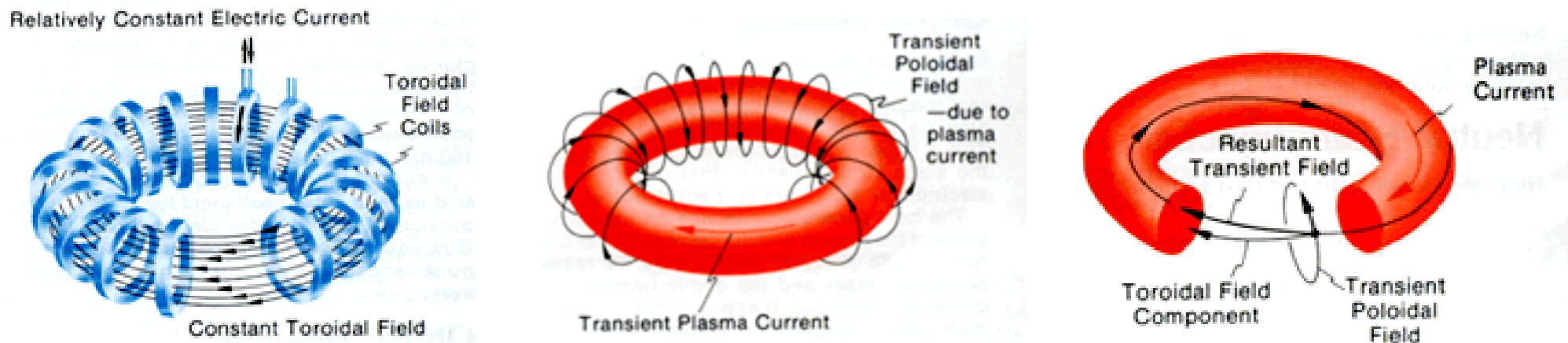
There is still particle and heat transport across the magnetic field, although it is much slower than without the field.

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

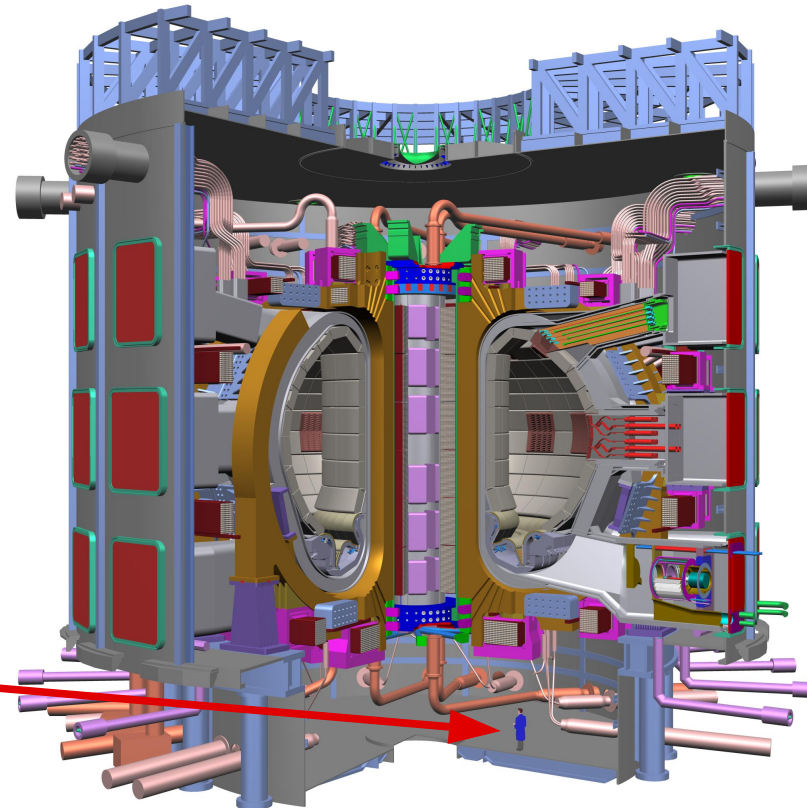
ITER = International Experimental Thermonuclear Reactor

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.

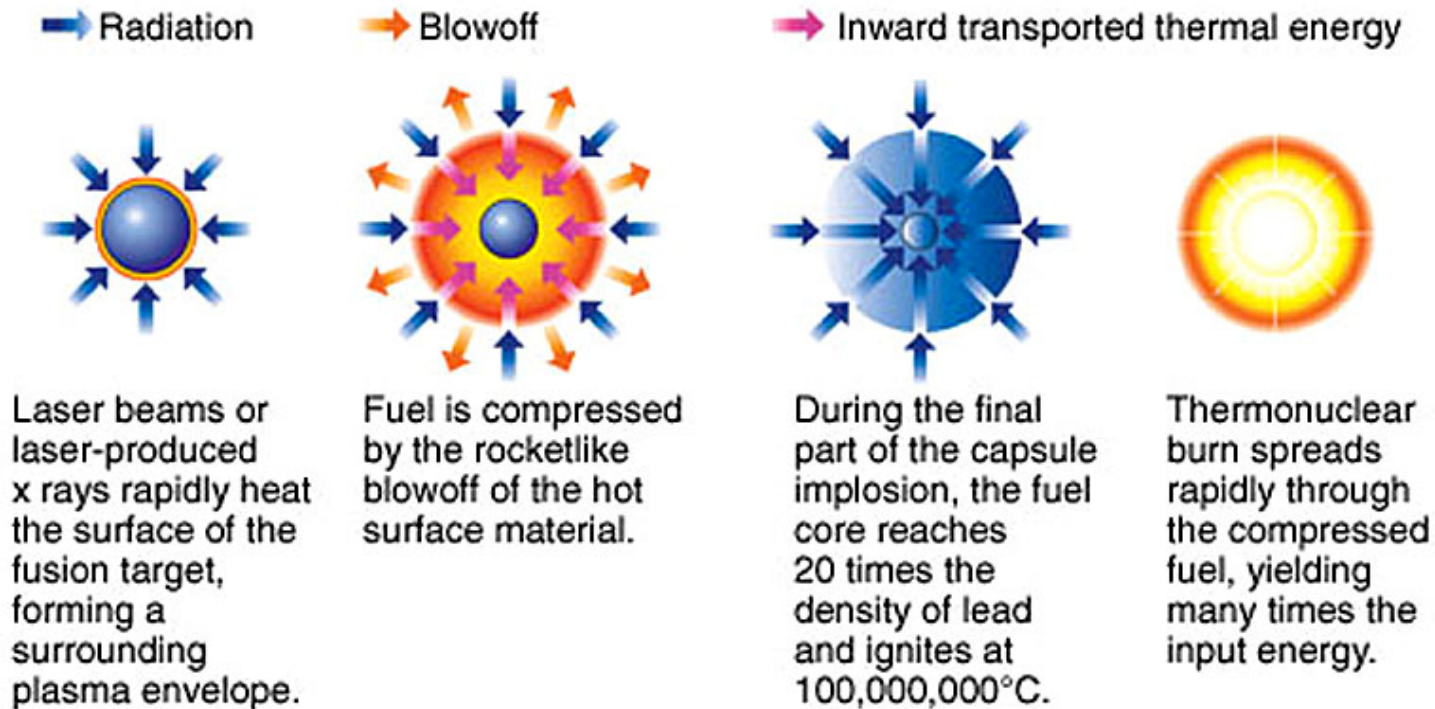
Expected to be operational ~ 2018, DT shots in 2026, cost \$10 billion to construct*.

For scale, there is a man



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

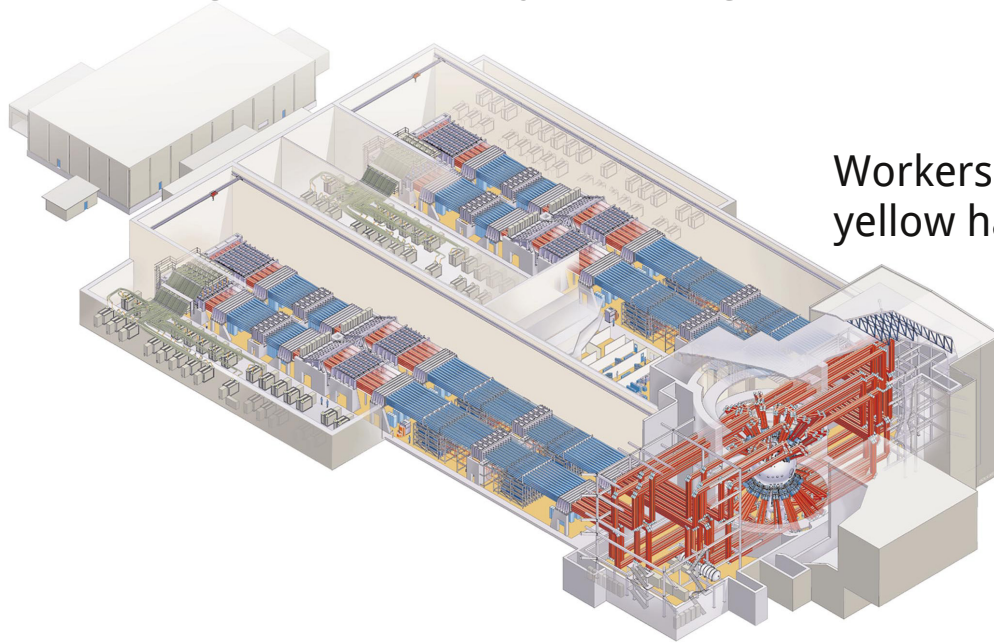
Doing it on Earth: Inertial confinement



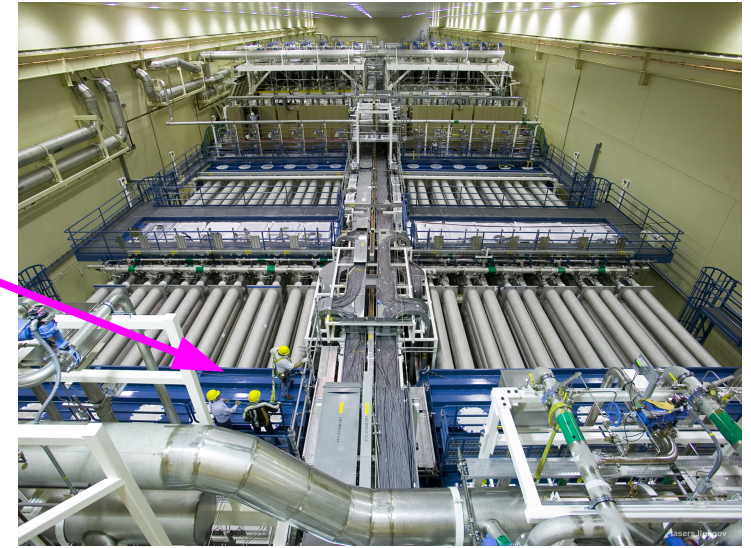
- Use light to boil off matter from a spherical pellet of fusion fuel. This ablation process causes the blowoff to expand, and the pellet to implode inward. Like a spherical rocket.
- The compressed fuel will hopefully reach high enough densities (hundreds of times that of liquids) and temperatures for 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 disassembly.

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.

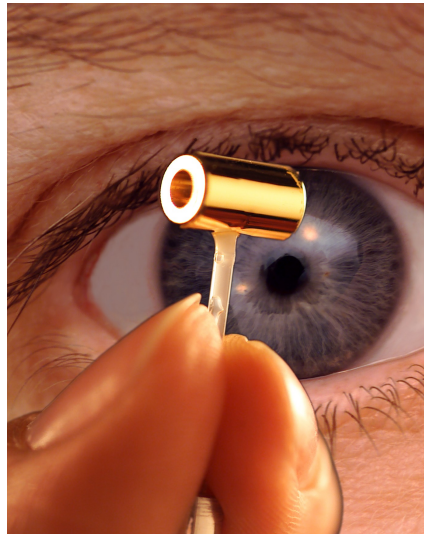


Workers w/
yellow hardhats

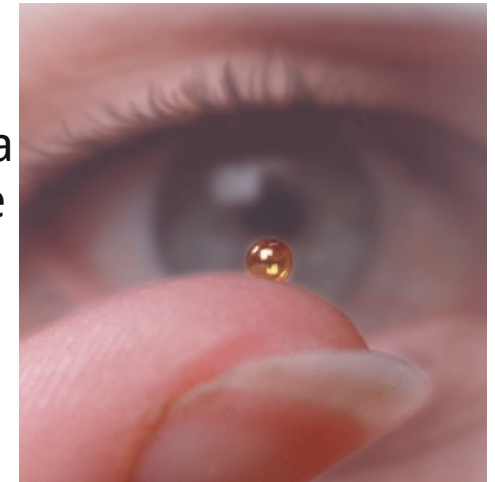


1.5 megajoules (360 Calories) of laser energy is deposited, over several nanoseconds, into:

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.

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 materials 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 hybrid:

Use fusion neutrons to breed fission fuel, and/or burn up fission waste into benign material

Summary: what fusion is and where we stand

- Nuclear 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!