Conceptual Physics

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Lesson X
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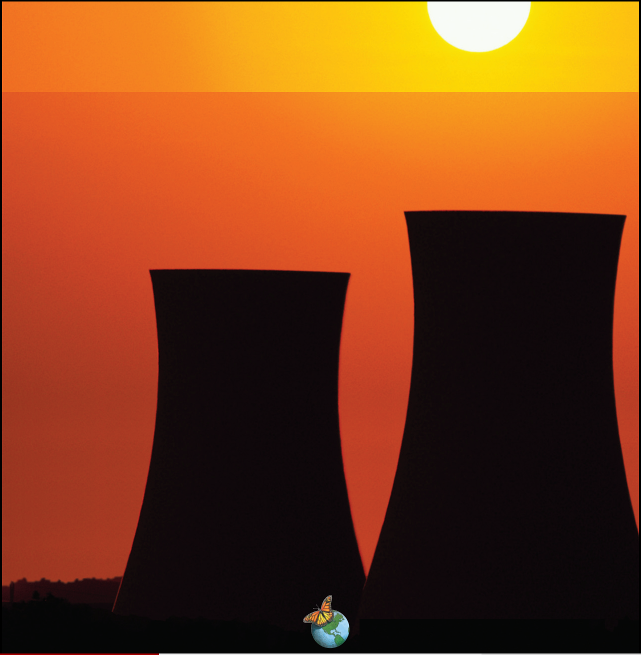

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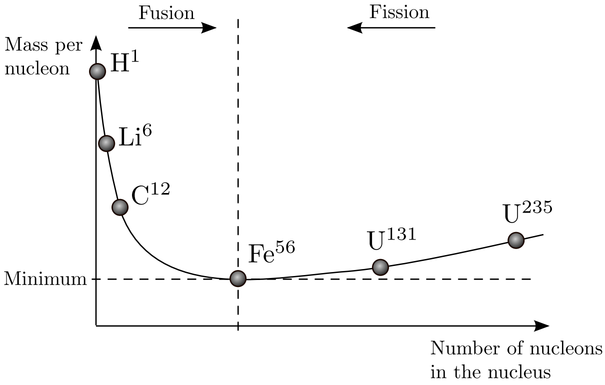
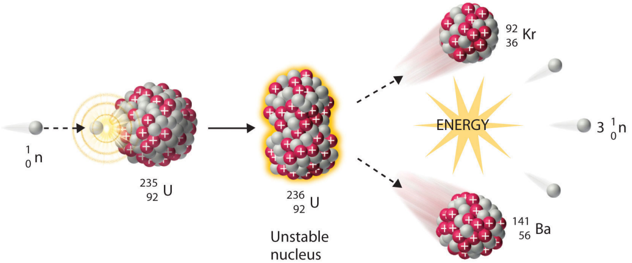
- For energy production
  two distinct processes involving nuclei can be harnessed
  1. fission ☞ splitting of a nucleus
  2. fusion ☞ joining together of two nuclei
- Mass per nucleon for different elements has minimum @ ^{56}Fe



- ^{56}Fe is *relatively* more tightly bound than the other nuclei
- Average binding energy *per nucleon* is greater for ^{56}Fe than for other nuclei
- For elements lighter than ^{56}Fe ☞ mass per nucleon decreases when combining nuclei to form more heavier elements
- For light elements ☞ energy is usually released in fusion reaction
- For elements heavier than ^{56}Fe ☞ mass per nucleus increases with increasing number of nucleons and energy is liberated in a fission reaction
- For any given mass or volume of fuel nuclear processes generate more energy than can be produced through any other fuel-based approach

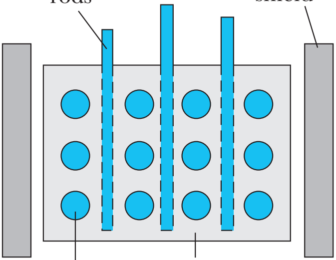
- Fission of uranium nucleus liberates large amount of energy which comes from changes in internal energy of reacting nuclei
- Splitting of uranium-235 releases over 3×10^{-11} J
  - Mass deficit for the reaction $^{235}\text{U} + n \to {}^{141}\text{Ba} + {}^{92}\text{Kr} + 3n$ is:
    $(140.91441 + 91.92616 + 2 \times 1.008665 - 235.04394)\,\text{u} = -0.18604\,\text{u}$
  - Since $1\ \text{u} = 1.66058 \times 10^{-27}$ kg and $E = mc^2$
    annihilation of 3.08934×10^{-28} kg of mass
    produces 2.78041×10^{-11} J of energy



- Only ^{235}U part of uranium (0.7%) undergoes fission
  when irradiated with slow neutrons
- ^{238}U (99.3%) will absorb fast neutrons becoming ^{239}U
  but it will not fission
- Neutrons must be *slow*
  because they have to stay around nucleus a while to be *captured*
- They don't really knock the ^{235}U appart during fission
  it is really more like they enter nucleus to form ^{236}U
  which is very unstable and undergoes fission
- During each fission ☞ about 3 n (on average) are produced
- Possibility of a chain reaction is then present
  except that these fission neutrons are fast
- So ☞ not only they fly past ^{235}U without causing further fission
  but they also get captured by ^{238}U
- We need way of slowing down neutrons produced in fission
- Moderating them and then letting hit more uranium

Modus operandi is as follows

- Arrange a series of uranium rods sitting in moderator



- You must make sure that:
  - moderator moderates ☞ slow neutrons
  - moderator does not absorb too many neutrons
  - moderator does not become radioactive

because it is also used for cooling

- For moderator to slow down n ☞ it must consist of light atoms
  (n would just bounce off heavy atoms without losing speed)
- H (as part of water) is excellent except that it absorbs n

$$\text{hydrogen} + \text{neutron} = \text{deuterium}$$

- So to use ordinary water
  one must eliminate some of the absorption of neutrons by ^{238}U
  by making the uranium rod richer in ^{235}U ("enrichment")
- This is a very expensive process
- Carbon (graphite) does not absorb neutrons
  but it is also pretty heavy so it doesn't moderate as well
- So ☞ if you use graphite you must enrich the uranium
- Heavy water (D_2O) is excellent
  it moderates as well as ordinary water and it doesn't absorb n
- *Reactors using heavy water don't need uranium enriched*
  they use natural mixture of ^{238}U and ^{235}U
- Neither water, graphite, or heavy water
  become radioactive when n pass through them

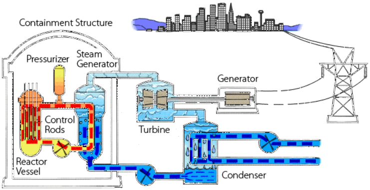
- In December 1942 ☞ Fermi constructed first nuclear reactor
- It used natural uranium (not enriched)
  a graphite moderator (to slow neutrons)
  and boron control rods (to control reaction by absorbing n)
- Stage was then set for building uranium bomb
- For the bomb ☞ one has *no moderator* ⇒ *no control rods*
  but pure ^{235}U (very expensive)
- 2 pieces of ^{235}U are brought together through small explosion
  and are irradiated with n from small radioactive source (in bomb)
- Each piece by itself is not enough to "go critical"
  but together they can sustain a chain reaction
  using small number of slow n emitted during fission
  and small probability that fast one will be captured by ^{235}U
- Unless you have almost pure ^{235}U ☞ this won't work

- First (test; code name Trinity) bomb was exploded in July 1945
- First ^{235}U bomb was dropped on Hiroshima on August 6, 1945
- 2nd bomb (Plutonium) was dropped on Nagasaki two days later
- Plutonium ($^{239}_{94}$Pu) also undergoes fusion with slow neutrons
- It is *not* found naturally
  but is made whenever ^{238}U is radiated with fast neutrons

$$^{238}_{92}\mathrm{U} + n \to {}^{239}_{92}\mathrm{U} \xrightarrow[\text{23 min}]{\beta^-\text{decay}} {}^{239}_{93}\mathrm{Np} \xrightarrow[\text{2.35 days}]{\beta^-\text{decay}} {}^{239}_{94}\mathrm{Pu}$$

- Plutonium is highly radioactive but has long half-life of $24,100$ yr
- It is lethal in *microgram* quantities (much less than a speck)
  due to both its radioactive and chemical properties
- *Terrible stuff!*

- There are 61 commercially operating nuclear power plants with 99 nuclear reactors in 30 states of U.S.
- Most common type in use in U.S. ☞ pressurized-water reactor



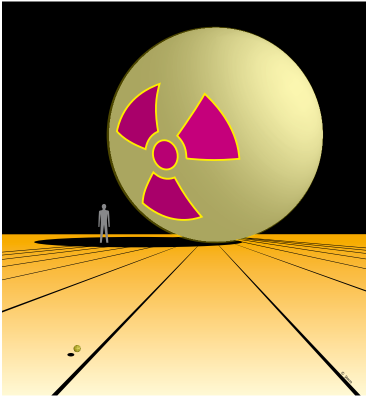
- Fission events in reactor core supply heat to water contained in primary (closed) loop which is maintained at high pressure to keep it from boiling
- This water also serves as moderator
- Hot water is pumped through a heat exchanger and heat is transferred to water contained in secondary loop
- Hot water in the secondary loop is converted to steam which drives a turbine-generator system to create electric power

Loss of coolant accident

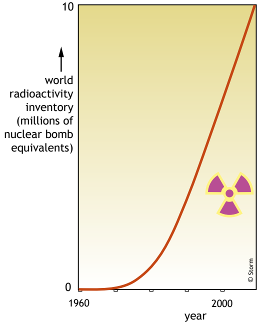
- Possible failure of pump or pipe would prevent water from cooling
- Unless emergency core cooling system went into effect
  core would melt down reactor in about 30 s
- If this so ☞ possible release of enormous amount of radioactivity
  to outside world
- To control power level control roads are inserted into reactor core
- Roads are made of material such as cadmium
  that absorb neutrons very efficiently

Radioactive waste disposal

- As a result of fission process
  radioactivity of nuclear fuel irreversibly increases a billionfold



- Pea in foreground (diameter 1 cm)
  represents original radioactivity of nuclear fuel
- Sphere in distance (diameter of 10 m) ☞ represents radioactivity
  of same amount of fuel 150 days after shutdown of reactor

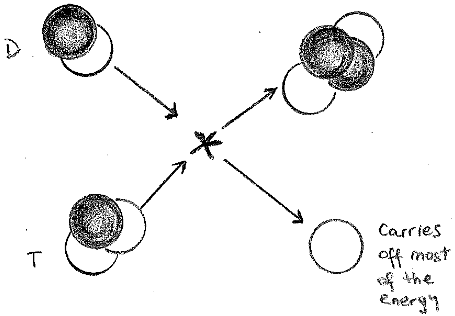


- Cumulative quantity of radioactivity generated worldwide by civilian nuclear power ☞ measured in nuclear bomb equivalents
- During 1960s, 1970s and 1980s
  quantity of radioactivity increased fast (exponentially)
- During last two decades ☞ growth has been almost linearly
  for global nuclear generating capacity leveled off during 1990s
- If world nuclear generating capacity increases in next decades
  world radioactivity inventory would grow exponentially again

- Reactions that take place in Sun cannot take place on Earth
- To hold H cloud together by gravitation (against expanding forces) until slow interaction $pp \to D + e^+ + \nu$ takes place
  requires a mass of material equal to $M_\odot$
- So if we would attempt to burn "protons" here
  "fire" would keep going out
- There are other nuclear fusion reactions
  which release enormous amount of energy
- These play no role in nuclear chemistry of the Sun because of tiny amounts of necessary materials present there
- We shall discuss two of these
- They involve isotopes of hydrogen, deuterium (D), and tritium (T)

- D-T reaction

$$D + T \to {}^4\text{He} + n + 6 \text{ billion Btu/oz of } (D + T)$$



- Compare to an energy release of $1,000$ Btu/oz of oil burnt
- D-D reaction
  - It is more complicated
  - it releases about 1/4 as much energy
  - It is very important in the very long run

Why D-T?

- To make a nuclear fusion reaction go
  nuclei must be brought close enough together to touch
- All nuclei are positively charged
  so we must accelerate them to high speeds
  to overcome effects of electric repulsion
- Since positive charge of nucleus increases with its mass (more p)
  it is clear why it is easiest to overcome electrical repulsion
  for lightest nuclei
- We have seen this in sun's life cycle
  where fusion of helium (charge +2 each) or carbon (+6 each)
  require higher temperature than fusion of hydrogen
- So ☞ we want to fuse hydrogen if we can
- But we have seen that p fusion goes only via weak interaction
- So ☞ we may inquire if fusion of D or T (same 1 + charge)
  can go via strong interaction
- Answer is yes!

What about availability?

- Deuterium is stable and very plentiful:
  1 out $6,000$ atoms of hydrogen in water is ^{2}H (a.k.a. deuterium)
- So ☞ a gallon of H_2O yields about a spoonful of heavy water D_2O
- It is relatively easy to separate off
- Tritium is another problem
- It is a radioactive gas ☞ decaying with a half-life of 12 years
  (to ^{3}He + electron + neutrino) so it doesn't occur naturally
- It can be produced in small quantities at ordinary nuclear reactors through the bombardment of lithium with neutrons

$$n + \mathrm{Li} \to^4 \mathrm{He} + \mathrm{T}$$

- At present ☞ world supply of lithium is equivalent (in eventual Btu)
  to that of all fossil fuels (a few hundred years)
- By that time ☞ one will have learned to run D-D reaction
  where resources are almost infinite (sea-water!)

Given this ☞ basic fact is...

- To overcome electrical repulsion ☞ D and T
  must approach one another at relative speed of about 1200 km/s
- For Sun ☞this involves heating D-mixture
  to temperatures of tens of millions of degrees K
- Such high temperatures are attainable on Earth
  in proximity of nuclear explosion
- Basic problem ☞ once D-T mixture is heated to $50 \times 10^{6\circ}$K
  how you get reaction going
  before mixture is cooled through contact with environment?
- International Thermonuclear Experimental Reactor (ITER)
  aims to show principle of producing more energy from fusion
  than is used to initiate it
- Something that has not yet been achieved in any fusion reactor