Exam 3: Wed. Dec. 1
Covers Chap. 13-16, part of 17

No HW assignment over Thanksgiving

Last time:

• Radioactive decay: alpha, beta, gamma
• Radioactive half-life
• Decay type understood in terms of number neutrons, protons.
• Understand in terms of weak interaction, Quark internal structure.
Energy production

• Hydroelectric plant
  - Uses 60,000 tons/sec water to produce 1,000 MW

Coal-burning plant
  - 10,000 tons coal/day to produce 1,000 MW

• Fission reactor
  - Uses 100 tons uranium/yr to produce 1,000 MW
Another comparison

A typical pellet of uranium weighs about 7 grams (0.24 ounces). It can generate as much energy as...

WORLD GENERATION BY FUEL

- Coal 39%
- Nuclear 16%
- Hydro 19%
- Gas 15%
- Oil 10%
- Other 1%

3.5 barrels of oil, or...
17,000 cubic feet of natural gas, or...
1,780 pounds of coal.
Stored energy

• Indicates that stored energy density can vary dramatically.

• How can so much energy be stored in the nucleus?

• Nuclear binding energy is very large

• This binding energy can be turned into other forms of energy using *fission* or *fusion*.
Fission and Fusion

• Fission:
  - Heavy nucleus is broken apart
  - Total mass of pieces less than original nucleus
  - Missing mass appears as energy $E=mc^2$

• Fusion
  - Light nuclei are fused together into heavier nuclei
  - Total mass of original nuclei greater than resulting nucleus
  - Missing mass appears as energy.
Fission

- Fission occurs when a heavy nucleus breaks apart into smaller pieces.
- Does not occur spontaneously, but is induced by capture of a neutron
Neutron capture

- When neutron is captured, $^{235}\text{U}$ becomes $^{236}\text{U}$
  - Only neutron # changes, same number of protons.

_Nucleus distorts and oscillate, eventually breaking apart (fissioning)_

Wed. Nov 24

Phy107 Lecture 33
Neutron production

- Fission fragments have too many neutrons to be stable.
- So free neutrons are produced in addition to the large fission fragments.
- These neutrons can initiate more fission events.
Chain reaction

- If neutrons produced by fission can be captured by other nuclei, fission chain reaction can proceed.
Neutrons

- Neutrons may be captured by nuclei that do not undergo fission
  - Most commonly, neutrons are captured by $^{238}$U
  - The possibility of neutron capture by $^{238}$U is lower for slow neutrons.

- The moderator helps minimize the capture of neutrons by $^{238}$U by slowing them down, making more available to initiate fission in $^{235}$U.
The critical mass

- An important detail is the probability of neutron capture by the $^{235}$U.
- If the neutrons escape before being captured, the reaction will not be self-sustaining.
- Neutrons need to be slowed down to encourage capture by U nucleus
- The mass of fissionable material must be large enough, and the $^{235}$U fraction high enough, to capture the neutrons before they escape.
The first chain reaction

- Construction of CP-1, (Chicago Pile Number One) under the football stadium in an abandoned squash court.
- A ‘pile’ of graphite, uranium, and uranium oxides.
- Graphite = moderator, uranium for fission.
- On December 2, 1942: chain reaction produced 1/2 watt of power.
  - 771,000 lbs graphite, 80,590 pounds of uranium oxide and 12,400 pounds of uranium metal,
  - Cost ~ $1 million.
  - Shape was flattened ellipsoid 25 feet wide and 20 feet high.
Pile assembly

Level 3
Graphite layers form the base of the pile.

Level 7
Uranium oxide pseudospheres start at level 7

Tenth layer of graphite blocks containing pseudospheres of uranium oxide

Level 19
The 19th layer of graphite covering layer 18 containing slugs of uranium oxide.
How much energy?

Binding energy/nucleon
~1 MeV less for fission fragments than for orig. nucleus

This difference appears as energy.

Energy/nucleon released by fission
Energy released

- $^{235}\text{U}$ has 235 total nucleons, so ~240 MeV released in one fusion event.

- $^{235}\text{U}$ has molar mass of ~235 gm/mole
  - So 1 kg is ~ 4 moles = $4 \times (6 \times 10^{24}) = 2.5 \times 10^{25}$ particles

- Fission one kg of $^{235}\text{U}$
  - Produce ~$6 \times 10^{33}$ eV = $10^{15}$ Joules
  - 1 kilo-ton = 1,000 tons of TNT = $4.2 \times 10^{12}$ Joules
  - This would release ~250 kilo-tons of energy!!!

- Chain reaction suggests all this could be released almost instantaneously.
Uranium isotopes

- $^{235}$U will fission.
- However after $^{238}$U absorbs neutron to become $^{239}$U, it beta decays (neutron changes to proton) to $^{239}$Np, $t_{1/2} = 23$ min.
- This quickly beta decays to $^{239}$Pu, $t_{1/2} = 2.3$ days.

Uranium, Neptunium, Plutonium

1941: discovered that Pu will fission.

Fission limited to $^{235}$U, $^{239}$Pu
Uranium isotopes

- Only the less abundant $^{235}\text{U}$ will fission.
- Natural abundance is less than 1%, most is $^{238}\text{U}$
Where does uranium come from?

- Uranium is one of the most abundant elements. However, concentrated uranium ores are found in just a few places, usually in hard rock or sandstone.
- For example, when uranium is mixed with granite that covers 60% of the Earth’s crust, there are approximately four parts of uranium per million, i.e. 999,996 parts of granite and four parts of uranium.

<table>
<thead>
<tr>
<th>Material</th>
<th>Concentration (ppm U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-grade orebody - 20% U</td>
<td>200,000 ppm* U</td>
</tr>
<tr>
<td>Low-grade orebody - 0.1% U</td>
<td>1,000 ppm U</td>
</tr>
<tr>
<td>Granite</td>
<td>4 ppm U</td>
</tr>
<tr>
<td>Sedimentary rock</td>
<td>2 ppm U</td>
</tr>
<tr>
<td>Average in Earth’s continental crust</td>
<td>1.4 ppm U</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.003 ppm U</td>
</tr>
</tbody>
</table>

*ppm = parts per million
Uranium ore processing

- Mechanically crush the ore
- Acid treatment to separate the uranium metal from rock.
- Purified with chemicals to leach out (dissolve) the uranium.
- The uranium-rich solution chemically separated waste and precipitated (condensed) out of the solution.
- Uranium-rich solution uranium is dried.
- Resulting powder is uranium oxide concentrate, $\text{U}_3\text{O}_8$, (yellowcake).
- Yellowcake is packaged into special steel drums similar to oil barrels. 400 kilograms when full.
- Hauled by truck to uranium refinery.
Uranium processing

- Still only natural (small) abundance of $^{235}\text{U}$.
- Most reactors need enriched Uranium.
- First step is chemical conversion
- Then isotope separation
- Then processing into fuel rods.
Uranium Hexafluoride

- Yellowcake converted to Uranium Hexafluouride
- Main use is separation of two main isotopes of uranium; $^{235}\text{U}$ has only 0.71% natural abundance.

- What is UF$_6$ like?
- White crystalline solid at room temperature
  Sublimes (turns to gas) at 56.5°C (133.8°F)
  Liquid only under pressures $> 1.5$ atmospheres $T > 64 ^\circ C$
Isotope separation

• How is the separation achieved?
• Several methods have been used:-
  - Gaseous diffusion
  - Electromagnetic isotope separation
  - Gas centrifugation
• Electromagnetic isotope separation, using $\text{UCl}_4$, was the original method used in the Manhattan project in a plant at Oak Ridge Tennessee.
• Gas diffusion and Gas centrifuge now produce more than 90% of the world's enriched uranium.
Gas diffusion enrichment

- UF$_6$ gas diffuses through etched foil.
- Lighter $^{235}$UF$_6$ molecules diffuse slightly faster than the $^{238}$UF$_6$ molecules. As the gas moves, the two isotopes are separated.
- Over 1000 stages are required to produce a UF$_6$ product with even 3–4% enrichment!
- US (Paducah, KT)
What about the $^{238}\text{UF}_6$?

- As of June 1998, the US Department of Energy (DOE) owned approximately 57,800 steel cylinders of depleted $\text{UF}_6$.
- The total radioactivity of depleted $\text{UF}_6$ is approximately 8.6 Ci/cylinder.
- Depleted $\text{UF}_6$ continues to be produced at the rate about 150 cylinders (2,100 short tons or 1,900 metric tons) per year.
Gas centrifuge enrichment

• Used in Canada

• Gaseous UF₆ is placed in a centrifuge.

• Rapid spinning flings heavier U–238 atoms to the outside of the centrifuge, leaving enriched UF₆ in the center

• Single centrifuge insufficient to obtain required U–235 enrichment.

• Many centrifuges connected in a ‘cascade’.

• U–235 concentration gradually increased to 3 – 5% through many stages.
Electromagnetic separation

- Original separation method used in Manhattan project
- Uses essentially a mass spectrometer.
Oak Ridge EM separation

- Control panels and operators for calutrons at Oak Ridge. The operators, mostly women, worked in shifts covering 24 hours a day.
- 10 kilograms or so of 90 percent U-235 that Oppenheimer thought necessary for a bomb.
Now what?

• All this was realized around 1939.
• Also when Hitler invaded Poland.
• By 1940, Europe occupied.
• 1941 Pu fission discovered.
• 1942 Controlled nuclear reactor
• 1943 Uranium enrichment at Oak Ridge, TN
• 1944-45 enriched Uranium/Plutonium arrive at Los Alamos
• 1945 Uranium bomb, Plutonium bomb, dropped
Uranium fission bomb

- Uranium ‘bullet’ fired into Uranium target
- Critical mass formed, resulting in uncontrolled fission chain reaction
Plutonium fission bomb

- Plutonium produced in reactor from $^{238}\text{U}$
- Required implosion.

![Image of Plutonium bomb]

Nuclear weapon of the "Fat Man" type, the bomb detonated over Nagasaki, Japan, in World War II. The bomb is 90 inches in diameter and 135 inches long. The second nuclear weapon to be detonated, it weighed about 10,000 pounds and had a yield equivalent to approximately 20,000 tons of high explosives.
Trinity test of Pu bomb

- Uranium fission bomb not tested before dropped.
- Pu bomb much more complex.
- Tested at Trinity site, New Mexico.
Active plutonium for bomb

Active material for the Trinity device is moved from the sedan that brought it to McDonald Ranch.

Box contains reactor-produced Plutonium
• Sgt. Herbert Lehr delivering plutonium core (or more probably half of it) to assembly room in McDonald Ranch farmhouse.

Test bomb being lifted to top of tower.
Jumbo

- Pu supply extremely limited
- failure could scatter tens of millions of dollars of Pu across New Mexico desert.
- Steel vessel to contain the explosion was built.
- Nicknamed “Jumbo,” a special 64-wheel trailer was required to carry it across the desert to Trinity site.
- As confidence in Pu bomb grew, Jumbo was not used.
• Tower and firing electronics assembly
Controlled Nuclear Reactors

- The reactor in a nuclear power plant does the same thing that a boiler does in a fossil fuel plant - it produces heat.

- Basic parts of a reactor:
  - Core (contains fissionable material)
  - Moderator (slows neutrons down to enhance capture)
  - Control rods (controllably absorb neutrons)
  - Coolant (carries heat away from core to produce power)
  - Shielding (shields environment from radiation)

- 1,000 megawatt light-water reactor has a core with ~ 75 tons of uranium ~ 200 fuel assemblies.
The Moderator

- Slow neutrons are more likely to cause fission events
- Most neutrons released in the fission process have energies of about 2 MeV
  - In order to sustain the chain reaction, the neutrons must be slowed down
- A moderator surrounds the fuel
  - Collisions with the atoms of the moderator slow the neutrons down as some kinetic energy is transferred
  - Most modern reactors use heavy water as the moderator
• Control rods absorb neutrons, taking them out of the reaction.
• Moderator present to slow neutrons for capture.
Unpressurized steam reactor

Control rod
Uranium fuel rod
Nuclear reactor
Molten sodium or liquid water under high pressure (carries heat to steam generator)

Steam turbine and electric generator
Condenser (steam from turbine is condensed by cold water)
Heat exchanger

Pump
Cold water
Warm water
Different reactor types

Reactor Types in Use Worldwide, January 2003

- Pressurized Heavy Water Reactors: 59%
- Boiling Water Reactors: 21%
- Gas Cooled Reactors: 7%
- Light Water Graphite Reactors: 4%
- Other: 1%
- Pressurized Water Reactors: 8%
The Fast Breeder Reactor (FBR) has a core of plutonium surrounded by rods of U–238. The U–238 nuclei absorb neutrons from the core and are transformed into plutonium (P–239). For every four atoms of plutonium that are used up in the core of the breeder, five new plutonium atoms are made from the U–238. Therefore, FBRs “breed” plutonium. Fast breeder reactors work at such a high temperature that they need a special coolant such as liquid sodium. In addition, they are not equipped with a moderator to slow down neutrons, and for this reason are called “fast” breeders.
Nuclear Waste

- What is all the fuss about nuclear waste?

- The atoms formed when uranium atoms are split up are usually very radioactive. The "used" fuel rods from a reactor [discarded when about 25% of the uranium has undergone fission] are kept in a cooling pond for months for the more intensely radioactive atoms to decay and release most of their energy. Then they have to be processed to separate "unused" uranium atoms from the remaining fission products that have to be stored safely in barrels, often in underground bunkers (see photo, right).

- Transmutation
Nuclear Fusion

- ‘Opposite’ process also occurs, where nuclei are fused to produce a heavier nucleus, but requires large initial energy input.
- Called nuclear fusion.
**Terrestrial fusion reactions**

- Deuterium = nucleus of (1 proton & 1 neutron)
- Tritium = nucleus of (1 proton & 2 neutrons)
- Two basic fusion reactions:
  - deuterium + deuterium $\rightarrow$ $^3\text{He} + n$
  - deuterium + tritium $\rightarrow$ $^4\text{He} + n$

*Energy is released as result of fusion:*
\[
D + T \rightarrow ^4\text{He} \ (3.5 \text{ MeV}) \ + \ n \ (14.1 \text{ MeV})
\]

Energy determined by mass difference
Routes to fusion

- Magnetic confinement in a torus (in this case a tokamak).
- The plasma is ring-shaped and is kept well away from the vessel wall.

Laser beams compress and heat the target; after implosion, the explosion carries the energy towards the wall.
Interior of Tokamak test reactor

- Vacuum inside torus.
- Plasma confined from walls by magnetic field.
- Fusion induced by providing input power.
Fusion reactors

Superconducting magnet

Plasma confinement torus

Proposed ITER fusion test reactor

Wed. Nov 24
Nova laser facility (Livermore)
Nova, cont.

- A short, intense shock causes the deuterium to form a hot plasma and, very briefly, become a conducting metal.
- Fusion then results
Fusion bombs

Fission bombs worked, but they weren't very efficient.
- Fusion bombs, have higher kiloton yields and efficiencies, But design complications
- Deuterium and tritium both gases, which are hard to store.
- Tritium is in short supply and has a short half-life,
- Deuterium or tritium has to be highly compressed at high temperature to initiate the fusion reaction.

- Storeage: make solid lithium-deterium compound.
- Tritium decay proble: neutrons from a fission reaction could produce tritium from lithium
- Stanislaw Ulam recognized that the majority of radiation given off in a fission reaction was X-rays, and that these X-rays could provide the high temperatures and pressures necessary to initiate fusion.
- Therefore, use fission bomb to initiate fusion.
• The fission bomb imploded,
• These X-rays heated the tamper, preventing premature detonation of the lithium deuterate.
• The heat caused the tamper to expand and burn away, exerting pressure inward against the lithium deuterate.
• The lithium deuterate was squeezed by about 30-fold.
• The compression shock waves initiated fission in the plutonium rod.
• The fissioning rod gave off radiation, heat and neutrons.
• The neutrons went into the lithium deuterate, combined with the lithium and made tritium.
• The combination of high temperature and pressure were sufficient for tritium-deuterium and deuterium-deuterium fusion reactions to occur, producing more heat, radiation and neutrons.
• The neutrons from the fusion reactions induced fission in the uranium-238 pieces from the tamper and shield.
• Fission of the tamper and shield produced even more radiation and heat.
• The bomb exploded.