L 37 Modern Physics [4]

- Nuclear physics
  - what’s inside the nucleus and what holds it together
  - what is radioactivity, halflife
  - carbon dating
- Nuclear energy
  - nuclear fission
  - nuclear fusion
  - nuclear reactors
  - nuclear weapons

Radioactivity

- Some nuclei are unstable and spontaneously emit particles at random times
  - Alpha particles \( ^4He \) (helium nucleus)
  - Beta particles – energetic electrons
  - Gammas - energetic photons
- The beta particles (electrons) come from a process called beta decay, in which a neutron decays into a proton, an electron and an antineutrino (note that charge is conserved!)
  \[
  _0^1n \rightarrow _1^1p^+ + e^- + \bar{\nu}
  \]

Nuclear Reactions and E = mc\(^2\)

Einstein: a little mass goes a long way

Energy is released in the fission (breakup) of a heavy nucleus by neutron bombardment

\[
_0^1n + ^{239}_{94}Pu \rightarrow ^{96}_{38}Sr + ^{143}_{56}Ba + 4_0^1n
\]

mass = 240.06 units mass = 239.86 units

The extra mass is converted into kinetic energy, which is mostly in the neutrons.

Biological effects of nuclear radiation

- Nuclear reactions can produce alphas, betas, neutrons and gamma radiation (particles or photons)
- Nuclear radiation is ionizing radiation, i.e., energetic enough to knock electrons out of atoms or molecules
- Ionizing radiation is potentially harmful to humans because the ionization it produces can alter significantly the structure of molecules within a living cell which can lead to alterations of the cell (make them cancerous) or to the death of the cell

Hazards of radiation

- The hazards of radiation can be minimized by limiting overall exposure
- The effects of absorbed doses or ionizing radiation is measured in a unit called the rem.
- The effects of radiation exposure are
  - Short term or acute effects appearing within a matter of minutes of exposure
  - Long-term effects that may appear in years, decades or even in future generations

Average radiation doses received by a US resident

<table>
<thead>
<tr>
<th>Source of radiation</th>
<th>dose in mrem/yr*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Natural Background radiation</strong></td>
<td></td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>28</td>
</tr>
<tr>
<td>Earth and air</td>
<td>28</td>
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<tr>
<td>Internal radioactive nuclei</td>
<td>39</td>
</tr>
<tr>
<td>Inhaled radon</td>
<td>200</td>
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<tr>
<td><strong>Man-made radiation</strong></td>
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<tr>
<td>Medical / dental x-rays</td>
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</tbody>
</table>

*Current federal standards limit exposure to 500 mrem/yr
**Radiation sickness**

- This is the general term applied to the acute effects of radiation
- A dose less than 50 rem causes no short term ill effects
- A dose of 50 – 300 rem **at one time** brings on radiation sickness
- A whole body dose of 400 – 500 rem is lethal for about 50% of people exposed
- Whole body doses greater than 600 rem results in death for almost all individuals

**Nuclear Physicists**

- Otto Hahn and Lise Meitner: Discovered fission
- Marie Curie: Discovered Radioactivity
- Enrico Fermi: “Father of the Atomic bomb”
- Edward Teller: “Father of the Hydrogen bomb”

**Energy from the nucleus**

- Huge amounts of energy are given off in two nuclear processes
  - **Nuclear fission**: splitting a heavy nucleus in two
  - **Nuclear fusion**: fusing two light nuclei into one

**A lot of energy from a little mass**

- The energies released when a large nucleus undergoes fission or small nuclei undergo fusion are enormous compared to chemical energies (e.g. burning fossil fuel)
- When Uranium splits apart about 0.1% of its mass is converted into energy
- Pound for pound, nuclear reactions release about 10 million times more energy than chemical reactions
- 1 pound Uranium $\rightarrow$ 1 million gallons of gasoline

**Fission**

- To split a uranium nucleus apart takes energy
- A neutron hitting a uranium nucleus can cause it to split
- A neutron can split U-235 into Cs-143 and Rd-90 plus a few extra neutrons

**The nuclear chain reaction**

- When U-235 splits, on average 2.5 neutrons are released
- These neutrons can then go on to cause other U-235’s to split, this resulting in a chain reaction
- This can result in a catastrophic process with enormous energy released.
Reactor or Bomb

- If the energy released in a nuclear chain reaction is allowed to proceed in a controlled way, then this can be used as an energy source → nuclear reactor
- If the chain reaction occurs in an uncontrolled manner then you have → atomic bomb
- Enrico Fermi produced the first nuclear reactor under the west stands of Stagg Field at the University of Chicago in 1942

Nuclear reactors

- The fuel elements contain the fissile fuel in the form of rods of 1 cm diameter. There may be thousands of such rods stacked together in the reactor core
- The most common fuel is enriched U-235
- Some type of moderator material is also used to slow down the neutrons to make their capture more efficient

Inside a nuclear power plant

Nuclear Power Plant

Steel and Concrete Containment vessel

Reactor operation

- The reactor is usually operated in the so-called critical state in which each fission leads to only one additional fission.
- In the critical state the reactor produces a steady output of electrical energy
- The reactor is designed not to go into the supercritical state – in this state the reactor produces an uncontrolled and increasing amount of energy which can cause it to overheat and lead to meltdown.

Controlling the nuclear reactor

- To keep the reactor in the critical state the operators adjust the control rods
- The control rods can be moved into or out of the reactor core. They contain an element, such as cadmium or boron which absorbs neutrons.
- If the reactor is getting too hot, the control rods are pushed into the core to slow down the chain reaction
- The heat generated within the fuel rods is carried away by water surrounding the rods
To start the reactor the control rods are pulled out of the core

To stop the reactor the control rods are pushed into the core

Pros and Cons of Nuclear energy

**Advantages**
- Plentiful fuel
- No greenhouse gases
- No poisonous emissions
- Non-polluting
- Efficient power production

**Disadvantages**
- Must deal with nuclear waste
- Possibility of catastrophic accident with long term effects*
- Expensive to build
- Can be used to enrich uranium for bombs

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* -- US – 1979, Three mile Island, Pennsylvania
- World- 1986, Chernobyl, Ukraine (80 killed within one week of accident)
-- Japan -2011 caused by Tsunami
  - Negative spin – big disaster – no more nuclear power plants
  - Positive spin – even with Tsunami, no one killed, build more plants

The atomic (fission) bomb

- The key is to achieve a critical mass of fissionable material
- If a critical mass can be achieved than an self-sustained uncontrolled reaction occurs
- To achieve critical mass (60 kg), 2 lumps (7 in diameter ball ) of a non-critical mass of U-235 are brought together quickly using a cannon
- When the U-235 becomes supercritical, a catastrophic fission will quickly turn into a fireball
Nuclear Fusion

Two light nuclei (like hydrogen) are combined into one, with a large release of energy.

If this is done with a large number of nuclei, the energy is released catastrophically as a Hydrogen Bomb.

The Hydrogen (thermonuclear fusion) Bomb

- A fusion bomb releases energy by fusing deuterium with tritium nuclei to form helium and neutrons.
- To achieve this, the hydrogen must be heated to 100 million °C using a fission bomb → thermonuclear.
- Thermonuclear fusion is what powers the stars.

Effects of a nuclear explosion

- The released neutrons produce the fireball by heating everything around them.
- The ultra hot fireball produces an intense flash of light, x-rays and gamma rays.
- The explosion creates a huge pressure surge → blast wave.
- Long after the blast there is the fallout → the creation and release of radioactive nuclei that are carried away in the air.

Controlled thermonuclear fusion

ITER- being built in France.

Will heat
Tritium gas to
100,000,000 K

We will go over the final exam practice questions on Wednesday and Friday.