Nuclear (Part II):

weapons

Physics of Modern Devices

March 25, 2020
Outline

- Last Time: Part I
  - Overview Nuclear Physics/Nuclear Structure
  - Some other “devices” which use nuclear physics
    - Carbon dating (based on beta decay of carbon isotope $^{14}$C)
    - Smoke detectors (based on alpha decay of Americium).

- Today: Part II
  - Nuclear Fission Weapons
  - Nuclear Fusion Weapons
  - Radiation detectors
  - Radiation levels
Nuclear Weapons

- *Nuclear weapon is the most destructive technology ever developed.*
- They (the nuclear weapons) release enormous amounts of energy
- They produce incredible temperatures
- They produce radioactive fallout
- They are relatively hard to make
- They use *chain reactions*

Terminology:
- atomic bombs (A-bombs)
  - Fission weapon
- hydrogen bombs (H-bombs)
  - Fusion weapons
Nuclear Fission

- Large nuclei can break up when struck
  - Collision knocks nucleons out of stable equilibrium.
  - Hard collisions are best at inducing fission.
- Neutrons make ideal projectiles for inducing fission. Why?

Originally discovered by E. Fermi et al., but misinterpreted. Correctly interpreted by Lize Meitner and others.
Chain Reaction

- Neutrons can induce fission
- Induced fission releases more neutrons
- This cycle can repeat if many nuclei are available – *chain reaction*!
- Each fission releases energy
  - Many fission events release unimaginable amounts of energy within very short time;
  - Sudden energy release produces immense explosion.
Requirement for a Bomb

- Initial neutron source
- Fissionable material (allowing induced fission)
- Fissions must release additional neutrons (> 1)
- Material must use fissions efficiently (critical mass)
Fissionable Materials

- $^{235}\text{U}$ and $^{239}\text{Pu}$ are fissionable materials.
- $^{235}\text{U}$ is rare ($\sim 0.7\%$ occurrence in natural uranium ore) and must be separated from $^{238}\text{U}$.
- $^{239}\text{Pu}$ is made by exposing $^{238}\text{U}$ to neutrons:
  - The bomb which was dropped at Nagasaki (Fat Man) was a plutonium bomb.
  - Not enough Pu-239 exists in nature to make a major weapons supply, but it is easily produced in breeder reactors.
Uranium

- The fission of U-235 in reactors is triggered by the absorption of a low energy neutron, often termed a "slow neutron" or a "thermal neutron".

$$\text{Example: } \quad ^{1}_0 n + _{92}^{235}U \rightarrow ^{236}_92 U^* \rightarrow X + Y + \text{neutrons}$$

- U-235 nucleus captures slow moving neutron
- Formation of U-236* (lasts $10^{-12}$s) and excess energy causes nucleus to undergo violent oscillations
- Nucleus splits into two fragments emitting several neutrons in the process
Nuclear Fission

- If a massive nucleus like uranium-235 breaks apart (fissions), then there will be a net yield of energy.
  - The sum of the masses of the fragments will be less than the mass of the uranium nucleus.
  - If the mass of the fragments is equal to or greater than that of iron at the peak of the binding energy curve, then the nuclear particles will be more tightly bound than they were in the uranium nucleus, and that decrease in mass comes off in the form of energy.
Problem

- Let’s estimate the disintegration energy, $Q$, released in a typical fission process.
- Then let’s calculate the total energy released if 1kg of U-235 undergoes fission.
Answer

Part 1:
Binding energy / nucleon for heavy nuclei
is ~ 7.6 MeV (A ~ 240)
For intermediate mass nuclei ~ 8.5 MeV
\[ Q = (240 \text{ nucleons}) \cdot (8.5 \text{ Mev/nucleon} - 7.5 \text{ MeV/nucleon}) \]
\[ Q \approx 220 \text{MeV} \]

Part 2:
1 kg \(^{235}U\)
\[ N = \frac{6.02 \times 10^{23} \text{nuclei/mol}}{235 \text{g/mol}} \cdot 10^3 \text{g} = 2.56 \times 10^{24} \text{nuclei} \]
\[ E = NQ = (2.56 \times 10^{24} \text{nuclei}) \cdot (220 \text{MeV}) = 5.6 \times 10^{26} \text{MeV}! \]
1MeV = 4.45 \times 10^{-20} \text{kWh}
\[ So, E = 2.5 \times 10^7 \text{kWh} \]
This keeps a 100W lightbulb going 30,000 years!
The most probable fission events correspond to non-symmetric events (events for which fission fragments have unequal masses)

Most probable events correspond to fission fragments with mass number $A \sim 140$ and $A \sim 95$

Fragments that have large excess of neutrons are unstable
Avg. Fission Yield

\[
\frac{Q_{\text{avg}}}{M_{\text{uranium}} + M_n} = \frac{220\text{MeV}}{218896.8\text{MeV} + 939.6\text{MeV}} \approx 0.1\%
\]
Nuclear Fusion

- If light nuclei are forced together, they will fuse with a yield of energy, because the mass of the combination will be less than the sum of the masses of the individual nuclei.

- If the combined nuclear mass is less than that of iron at the peak of the binding energy curve, then the nuclear particles will be more tightly bound than they were in the lighter nuclei, and that decrease in mass comes off in the form of energy.

- For elements heavier than Fe, fission will yield energy. For elements lighter than Fe, fusion will yield energy.

Example:
Proton-proton cycle
25 MeV energy released

\[
\begin{align*}
_{1}^{1}H +_{1}^{1}H & \rightarrow _{1}^{2}H + _{0}^{0}e + \nu \\
_{1}^{1}H +_{1}^{2}H & \rightarrow _{2}^{3}He + \gamma \\
_{2}^{3}He +_{2}^{3}He & \rightarrow _{2}^{4}He + _{1}^{1}H + _{1}^{1}H
\end{align*}
\]
Deuterium-Tritium

- The most promising of the hydrogen fusion reactions which make up the deuterium cycle is the fusion of deuterium and tritium.
- One of the major problems in obtaining energy from nuclear fusion is that the Coulomb repulsion force must be overcome before they can fuse.
- Accomplished by heating the fuel to extremely high temperatures
- Deuterium is available in large quantities from lakes and oceans and is inexpensive to extract
- Tritium is radioactive ($T_{1/2} = 12.3$ years) and undergoes beta decay to He-3 and must be artificially produced.

\[
\begin{align*}
\text{\(^2\text{H} + \text{\(^2\text{H}\)} \rightarrow \text{\(^3\text{He}\)} + \text{\(^1\text{n}\)}} & \quad Q = 3.27\text{MeV} \\
\text{\(^2\text{H} + \text{\(^2\text{H}\)} \rightarrow \text{\(^1\text{H}\)} + \text{\(^1\text{H}\)}} & \quad Q = 4.03\text{MeV} \\
\text{\(^2\text{H} + \text{\(^3\text{H}\)} \rightarrow \text{\(^4\text{He}\)} + \text{\(^1\text{n}\)}} & \quad Q = 17.59\text{MeV}
\end{align*}
\]
Fusion Reactors

- The enormous amount of energy released in fusion
- Used in Nuclear Reactors
Problem

- Fusion of two deuterons:
  - The separation between two deuterons must be at most $\sim 10^{-14}$ m in order for the attractive nuclear force to overcome the repulsive Coulomb force.
    - Let’s calculate the potential energy (barrier) due to the repulsive force.
  - Next, let’s estimate the effective temperature required in order for the deuteron to overcome the potential barrier.
    - Assume $3/2 k T$ thermal kinetic energy per deuteron.
Answer

Part 1:
Potential Energy:
\[ V = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r} \]
\[ = \frac{1}{4\pi(8.85 \times 10^{-12} \frac{C^2}{Nm^2})} \frac{(1.6 \times 10^{-19} C)^2}{10^{-14} m} = 2.3 \times 10^{-14} J = 0.14 \text{MeV} \]

\( (6.24 \times 10^{12} \text{MeV} = 1J) \)

Part 2:
\( V \) is the Coulomb energy for a pair of deuterons.
So per deuteron it is \( 0.14 \text{MeV}/2 = 0.07 \text{MeV} = 1.1 \times 10^{-14} J \)

\[ 1.1 \times 10^{-14} J = \frac{3}{2} kT \]

So,
\[ T = \frac{2}{3} \frac{1.1 \times 10^{-14} J}{1.38 \times 10^{-23} J/K} = 5.3 \times 10^8 K!! \]

This is greater than the inside of the sun! (2 million K)
History 1

Hiroshima

- On August 6, 1945, a uranium fission bomb was detonated over the Japanese city of Hiroshima.
- The bomb, called "Little Boy" was a "gun-type" device which used an explosive charge to force two sub-critical masses of U-235 together.
- 28 inches in diameter and 120 inches long
- An explosive force of some 20,000 tons of TNT by converting about 1 gram of matter into energy.
- This could be accomplished with a sphere of U-235 about the size of a baseball.
- This kind of device had never been tested
- No device like this has been used since, making the estimates of radiation exposure at Hiroshima very difficult.
- The bomb was triggered to explode at a height of 550 meters (1800 ft), a height calculated to cause the widest area of damage.
- In the detonation of the uranium fission bomb over Hiroshima, about 130,000 people were reported killed, injured, or missing. Another 177,000 were made homeless.
The comparison unit for nuclear explosions which became most popular was the "ton of TNT".

One kilogram of mass converted to energy is equivalent to about 22 megatons of TNT.

\[
(1 \text{ kg}) c^2 = 9 \times 10^{16} \text{ joules} = 22 \text{ megatons TNT}
\]

\[
4.1 \times 10^9 \text{ joules} = 1 \text{ ton TNT}
\]

\[
(1 \text{ gm}) c^2 = 9 \times 10^{13} \text{ joules} = 22 \text{ kilotons TNT}
\]
History 2

Nagasaki

- On August 9, 1945 a plutonium fission bomb was detonated over the Japanese city of Nagasaki.
- The bomb, called "Fat Man", was 128 inches long and had a diameter of 60.5 inches.
- This kind of device had been tested less than a month before the drop, and was the subject of several other weapons tests after World War II.
- The explosive yield was about 20,000 tons of TNT, generated in about a microsecond.
- The bomb was triggered to explode at a height of 550 meters (1800 ft), a height calculated to cause the widest area of damage.
Blast Damage

- Blast damage from a nuclear weapon comes from the overpressure in the air and from winds which result from the pressures.
- For a 10 kiloton blast at the height where it would produce the most damage, severe damage to houses would occur out to 1.6 km and moderate damage to 2.4 km.
- A 10 kiloton blast would produce a fireball of about 300 m diameter and would cause moderate flash burns (second degree) at a range of about 2.4 km.
- For a 10 megaton blast, 1000 times as powerful, the severe damage would extend out about ten times as far, to 17.7 km.
- A 10 megaton blast would create a fireball about 4.8 km and moderate flash burns to 32 km.
- Accompanying the blast is a burst of neutrons and gamma rays, as well as lingering residual radiation from radioactive fallout.
Radioactive Fallout

- The highly radioactive fission byproducts are released into the atmosphere and spread over a wide area.
- Radioactive fallout in the form of fine particulate matter is particularly dangerous because it can be ingested, bringing alpha and beta emitters into the body where they can do much more damage.
Radiation Detectors

- Nuclear radiation is *ionizing radiation* and can be detected from the ionizing events they produce.

- Ionization Counters
  - Example: Geiger Counters

- Scintillation Counters

- Particle Track Devices
  - More on these devices next week …
Geiger Counter

- Wire inside a gas-filled cylinder; wire at a high positive voltage.
- When a high energy particle enters the cavity and ionizes a few air molecules, the free electrons are accelerated toward the wire.
- In the process, those electrons ionize many more air molecules, producing a current pulse.
- Survey meters often convert the current pulses into audible clicks.
Scintillation Counter

- **Scintillator**: a substance which emits light when struck by an ionizing particle.
- Electrons from the ionizing event are trapped into an excited state and emit a photon when they decay to the ground state.
- **Photomultiplier tubes** are used to intensify the signal from the scintillations.
  - electrons being produced as a consequence of the photoelectric effect.
  - electrons are multiplied by the process of secondary emission.
- The magnitude of the output pulse from the photomultiplier is proportional to the energy loss of the primary particle.
From last time …

**Alpha:**
- Range is less than a tenth of a millimeter inside the body
- Its main radiation hazard comes when it is ingested into the body
- It has great destructive power within its short range
  - In contact with fast-growing membranes and living cells, it is positioned for maximum damage.
- Not suitable for radiation therapy

**Beta:**
- High energy electrons have greater range of penetration than alpha particles, but much less than gamma rays
- The radiation hazard from betas is greatest if they are ingested

**Gamma:**
- Most gamma rays are high energy and very penetrating
- It is the most useful type of radiation for medical purposes
- But the most dangerous
  - Ability to penetrate large thicknesses of material
Activity of Radioactive Source

- The curie (Ci) is a standard unit for measuring the activity of a given radioactive sample.
- It is equivalent to the activity of 1 gram of radium.
- 1 curie = amount of material that will produce $3.7 \times 10^{10}$ nuclear decays per second.
Absorbed Dose of Radiation

- The rad is a unit of absorbed radiation dose in terms of the energy actually deposited in the tissue.
- The rad is defined as an absorbed dose of 0.01 joules of energy per kilogram of tissue.
- Applies to all types of radiation and all types of materials.
- Does not account for potential effect on human body due to different types of radiation.
Biologically Effective Dose

- The biologically effective dose in rems is the radiation dose in rads multiplied by a "quality factor", which is an assessment of the effectiveness of that particular type and energy of radiation.
- Rem describes biological effect on humans by taking into account the effect on the human body due to different types of radiation.
- Applies to all types of radiation.
- Used as legal unit for exposure reports.
- For alpha particles the relative biological effectiveness (rbe) may be as high as 20, so that one rad is equivalent to 20 rems.
- For x-rays and gamma rays, the rbe is taken as one so that the rad and rem are equivalent for those radiation sources.
Intensity of Radiation

- The roentgen (R) is a measure of radiation intensity of X-rays or gamma rays.
- Does not describe biological effects of radiation to humans.
- It is formally defined as the radiation intensity required to produce an ionization charge of 0.000258 coulombs per kilogram of air.
- It is one of the standard units for radiation dosimetry, but is not applicable to alpha, beta, or other particle emission and does not accurately predict the tissue effects of gamma rays of extremely high energies.
- The roentgen has mainly been used for calibration of X-ray machines.
The millirem

- A person would get 1 mrem of radiation from
  - Three days of living in Atlanta
  - Two days of living in Denver (*Why?*)
  - About seven hours in some spots in the Espirito Santo State of Brazil.

- You increase your dose by a mrem by:
  - an average year of TV watching
  - a coast-to-coast airline flight
  - a year living next door to a normally operating nuclear power plant
Average Annual Dose

- 360 mrem
- Natural Background Sources:
  - Cosmic - from outer space
  - Terrestrial - rocks & soil, drinking water, and building materials
  - Radon - radium in soil & building materials decays to give off radon gas
    - hazard when inhaled
    - largest portion of background dose (~200 mrem/yr)
  - static electricity attracts radon to some items (polyesters & plastics)
  - Radon is a special case of terrestrial radiation. It is a gas that comes from the radioactive decay of radium which is present in soil and building materials. It can collect in basements and other poorly ventilated locations in a building.
- Internal - food you eat, air you breathe, & water you drink
Average Annual Dose

- Man Made Sources:
  - Medical - diagnostic, therapeutic
  - Consumer items
    - Televisions
    - Welding rods
    - Lantern mantles
    - Camera lenses
    - Dental Prostheses
    - Smoke detectors
    - Tobacco
    - Fertilizers
  - Other - Nuclear power, fallout
Typical Radiation Doses

**Annual Dose (millirem)**

- **5000**: Maximum permissible occupational exposure
- **1250**: Natural exposure in mountainous areas of Brazil
- **500**: Average occupational dose for hospital radiologists
- **200**: U.S. Average total exposure, natural and medical
- **170**: Proposed limit on population-average non-occupational radiation
- **120**: U.S. average natural radiation
- **00**: U.S. average, diagnostic medical exposure
- **00**: Statutory limit on radiation from operating nuclear power plant
Factors Influencing Bio Effects

- Total dose - the greater the dose the more severe the biological effects
- Dose rate - the faster the dose is received the less time the cell has to repair itself and the more severe the effect
- Type of radiation - neutrons are more damaging than betas or gammas
- Area of body exposed - the larger the area exposed, the greater the effect
- Location of exposure - the torso of the body contains critical organs so an exposure here has a greater effect than an exposure to the hands or feet
- Cell sensitivity - some types of cells are more sensitive than others
- Individual sensitivity - some individuals/age groups are more sensitive than others
Acute vs. Chronic Dose

- **Acute Doses:**
  - Large amount of dose in a short period of time
  - If great enough, radiation sickness develops with symptoms shown in organs or systems with rapidly dividing cells (bone marrow, gastrointestinal tract); severity depends on dose
  - **NO biological effects to humans seen at doses <10,000 mrem**

- **Chronic Doses:**
  - Small amount of radiation over a long period of time
  - **Examples:**
    - Background doses
    - Occupational doses
    - Medical and dental x-rays
  - *Human body handles a chronic dose better than an acute dose*
Biological Effects of Chronic Radiation Does

- **NO** detectable physical changes, but it may affect the DNA of the cell
- Possible effects to DNA in cells:
  - Somatic Effects - seen in person who receives chronic dose (examples: cancer, cataracts).
  - Genetic Effects - seen in future generations due to damage in reproductive cells.
Announcements

Homework 7: Due today

Homework 8: I will post it tonight

Presentations: I will post the schedule by Friday