Lecture 26

Nuclear Fission
Nuclear Fusion
Nucleon (Baryon) Number Conservation

We have seen that in a β decay, we can convert protons ↔ neutrons, but the number of nucleons is constant.

Nucleon number is always conserved in nuclear reactions.

When we get to higher energies and particle physics, we find that nucleons are an example of a more general group of particles called baryons, and baryon number is conserved, not nucleon number.
Nuclear Fission

Nuclear fission refers to splitting of nuclei into two or more fragments.

Example: Uranium 235 fissions when bombarded with neutrons. A simple model is shown below:

First absorb a neutron: \( n_{\text{thermal}} + ^{235}\text{U} \rightarrow ^{236}\text{U} \)

Because of the energy released in this reaction, the \(^{236}\text{U}\) ends up in an excited state, 6.546 MeV above the ground state.

This excited state fissions (splits) into two large fragments and two or three neutrons.
Nuclear Fission

Nuclei rarely fission into two equal halves. The distribution shown is for $^{235}\text{U}$. Examples:

$^{236}_{92}\text{U}^* \rightarrow ^{144}_{56}\text{Ba} + ^{89}_{36}\text{Kr} + 3n$

$^{236}_{92}\text{U}^* \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2n$

The energy released ("Q value") for fission of heavy nuclei like uranium is of order 200 MeV.

This energy corresponds to 0.1% of the initial rest energy. (Ditto for mass.)
Chain Reactions

If there is enough fissionable material arranged so that the 2 - 3 fission neutrons are likely to be captured and generate additional fissions, we have a chain reaction.

Like an avalanche? A virus?

In the cartoon, each fission leads to 2 successive fission. This leads to rapidly expanding energy production and an explosion (nuclear bomb).

For a power plant, we want each fission to lead to one additional fission, so that the power is roughly constant.

Check out mouse trap fission model! Chain reaction can be initiated by external neutron, or by spontaneous fission.
Nuclear Reactors

$^{235}\text{U}$ fission releases 2-3 energetic neutrons, which can then trigger further fission events.

However, slow ("thermal") neutrons are better at initiating fission in $^{235}\text{U}$ than fast neutrons.

For this reason, neutrons are slowed down ("thermalized") by repeatedly scattering off a material with light nuclei that don't absorb neutrons.

Commonly used neutron moderators: graphite and water.

To sustain a chain reaction in a reactor, the 0.7% $^{235}\text{U}$ in natural uranium must be enriched (using centrifuges) to about 3%.

The chain reaction is kept under control by inserting neutron absorbing materials (control rods).
Nuclear Reactors

The kinetic energy of the decay products is converted into heat, transported into a heat exchanger, used to turn turbines and generate electricity. The decay elements typically are stopped in the fuel, heating it up. They are cooled by liquid coolant, typically water.

Picture of reactor core. Why is there a blue glow in the water?
Nuclear Power Safety Issues

In the event of an interruption of normal operation, it is not enough to shut down the chain reaction:

- The reaction products are highly radioactive, and the heat generated is enough to melt not only the fuel rods, but the reactor vessel and everything else used to contain the radioactive material (“nuclear meltdown”).
- Whenever this happens (Chernobyl 1986, Fukushima 2011) huge amounts of radioactivity are released into the environment.

Spent fuel rods are a huge liability:

- For the first 10 to 20 years they produce enough heat to require constant cooling.
- For the next couple of thousand of years they are radioactive enough to be an extreme hazard for human health and the environment.
- They need to be constantly guarded (for thousands of years) to prevent them from falling into the hands of terrorists (or anybody, for that matter).
In nuclear warheads the objective is a chain reaction sustained by fast neutrons, such that most of the fissionable nuclei can fission before the fuel is ripped apart by the explosion.

So neither neutron moderators nor control rods are used.

However, the fast neutrons are not very efficient at inducing fission, so U warheads must be enriched much more highly (90% $^{235}\text{U}$).

Another fissionable material suitable for warheads is $^{239}\text{Pu}$, which is produced in nuclear reactors.

Uranium bomb “Little Boy” destroyed Hiroshima, Aug. 1945

Plutonium bomb “Fat Man” wiped out Nagasaki, Aug. 1945
Nuclear Fusion Reactions

1. Two protons combine to form a deuteron ($^2H$) ...

2. ... as well as a positron ($\beta^+$) and an electron neutrino ($\nu_e$).

3. A third proton combines with the deuteron, forming a helium nucleus ($^3He$) and emitting a gamma-ray photon.

4. Two $^3He$ nuclei fuse, forming a $^4He$ nucleus and releasing two protons.

Need extremely high temperatures to initiate fusion (overcome Coulomb repulsion!)

How much energy is released in $4(^1H) \rightarrow ^4He + 2\beta^+$?

The $\beta^+$ annihilate with electrons to release more energy, so we need to include this. Total energy released: 26.73 MeV.

While fission converts 0.1% of rest mass to energy, fusion converts 0.7%!
Fusion Energy Production Schemes

Sun/stars.
Photovoltaics!
This is available today.

Inertial confinement:
Livermore National Ignition Facility: 192 lasers with $5 \times 10^{14}$ W implode small H pellets.

Magnetic confinement:
Tokamaks
Stellerators
Magnetic mirrors

Moving target: Energy production is perpetually promised to be about 20-30 years away 😞. Don't hold your breath.
Nuclear Fusion and Life

- All heavy elements were formed by fusion. All life depends on it!
- Energy production inside the sun. All life depends on it!
- Hydrogen bomb. All life is threatened by it.
- Nuclear fusion power generation: Nobody alive today is likely to see it (IMHO).
- Cold fusion, bubble fusion: Pure nonsense - don’t waste your life studying it!