PHYS:1200 LECTURE 36 — ATOMIC AND NUCLEAR PHYSICS (4)

This last lecture of the course will focus on nuclear energy. There is an enormous reservoir of energy in the nucleus and it can be released either in a **controlled** manner in a nuclear reactor, or in an **uncontrolled** manner in a nuclear bomb. The energy released in a nuclear reactor can be used to produce electricity. The two processes in which nuclear energy is released – **nuclear fission and nuclear fusion**, will be discussed in this lecture. The biological effects of nuclear radiation will also be discussed.

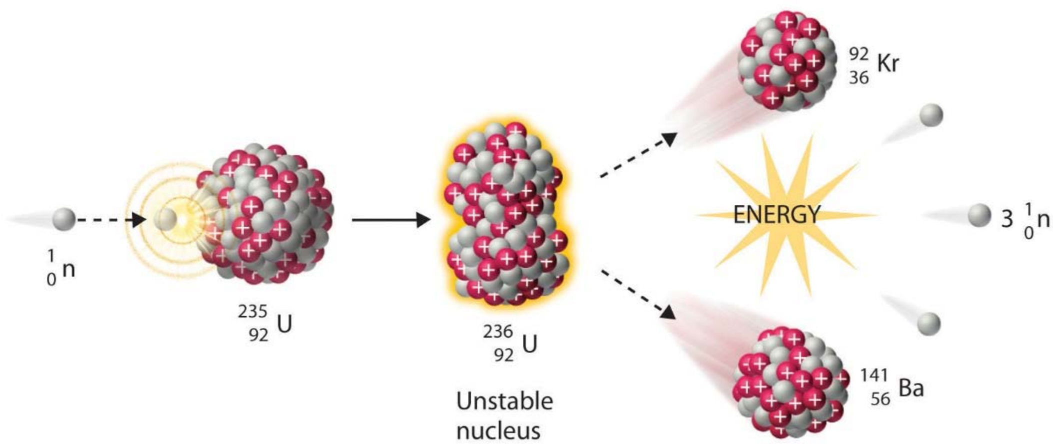
36-1. Biological Effects of Nuclear Radiation.—Radioactive nuclei emit alpha, beta, and gamma radiation. These radiations are harmful to humans because they are **ionizing radiation** that have the ability to remove electrons from atoms and molecules in human cells. This can lead to the death or alterations of cells. Alteration of the cell can transform a healthy cell into a cancer cell. The hazards of radiation can be minimized by limiting ones overall exposure to radiation. However, there is still some uncertainty in the medical community about the possibility the effect of a single radioactive particle on the bottom. In other words, are the effects cumulative, or can a single exposure lead to cancer in the body.

Exposure to radiation can produce either short term effects appearing within minutes of exposure, or long term effects that may appear in years or decades or even in future generations due to changes in DNA. The effects of absorbing ionizing radiation is measured in a unit called **the rem**. Current federal standards limits a person's exposure to 500 millirems per year. Short of living at the bottom of a deep mine, it is impossible to completely eliminate exposure to radiation, since it is present in the ground and air and there is a constant influx of cosmic radiation. Exposure can be minimized to an extent by limiting the number of medical and dental x-rays one has, as well as CAT scans and other forms of radiation used in nuclear medicine. In the unfortunate situation that one is exposed to an acute dose of radiation, the immediate result is **radiation sickness.** One might receive an acute dose, for example, in a nuclear power plant accident. On average, a radiation dose less than 50 rems causes no short term effects. A dose in the range of 50-300 rems results in radiation sickness. The symptoms of radiation sickness are nausea and vomiting. A whole body dose of 400-500 rems is lethal in about 50% of people who are exposed. A whole body dose greater than 600 rems is lethal in 100% of individuals. In the worst nuclear disaster in history at the Chernobyl reactor in the Ukraine, 28 rescue and fire fighters died from acute radiation exposure.

36-2 Energy from the Nucleus.—Nuclear energy is released in two processes:

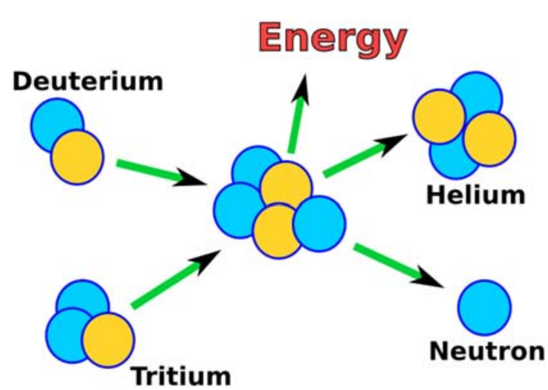
- nuclear fission
- nuclear fusion.

a. Nuclear fission.—In **nuclear fission,** a heavy nuclei splits into smaller fragments and individual neutrons which carry most of the energy in the form of kinetic energy. This is illustrated in the diagram below. Fission of U-235 is initiated by a neutron which hits the nucleus causing it



to become unstable. The unstable nucleus responds by splitting into Kr-92 and Ba-141 with the emission of 3 neutrons that carry off most of the liberated energy.

b. Nuclear fusion. In **nuclear fusion**, two light nuclei collide and fuse together to form one heavier nuclei as illustrated on the right. Deuterium and tritium fuse together to form a helium nucleus (alpha particle) and one neutron. Since both deuterium and tritium are positively charged, they must be brought together at tremendous speeds to get close enough for the short range nuclear force to fuse them together. Nuclear fusion is the energy source for all stars. The core of a star is at an extremely



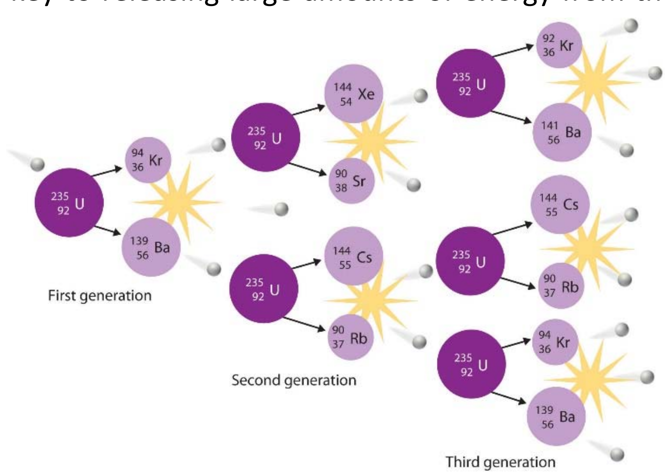
high temperature (15 million degrees C) due to the inward pressure of the gravitational attraction of its mass. At this temperature, protons move with high enough speeds to collide and fuse forming helium. Heavier elements are formed by the fusion of lighter elements.

c. Conversion of mass into energy, $E = mc^2$, in nuclear transformations.—The energies released in nuclear transformations are orders of magnitude larger that the energies involved in chemical transformations. Pound for pound, **nuclear reactions release about 10 million times more energy than chemical reactions.** The energy content of 1 pound of uranium is equivalent to that of 1 million gallons of gasoline. The energy released in nuclear reactions is due to the conversion of mass into energy according to **Einstein's famous equation** shown above. An example is provided by the fission of plutonium into strontium-96 and barium- 143 when bombarded by neutrons:

$$\underbrace{{}^{1}_{0}n + {}^{239}_{94}Pu}_{mass\,=\,240.06\,units} \rightarrow \underbrace{{}^{96}_{38}Sr + {}^{143}_{56}Ba + {}^{1}_{0}n}_{mass\,=\,239.86\,units}$$

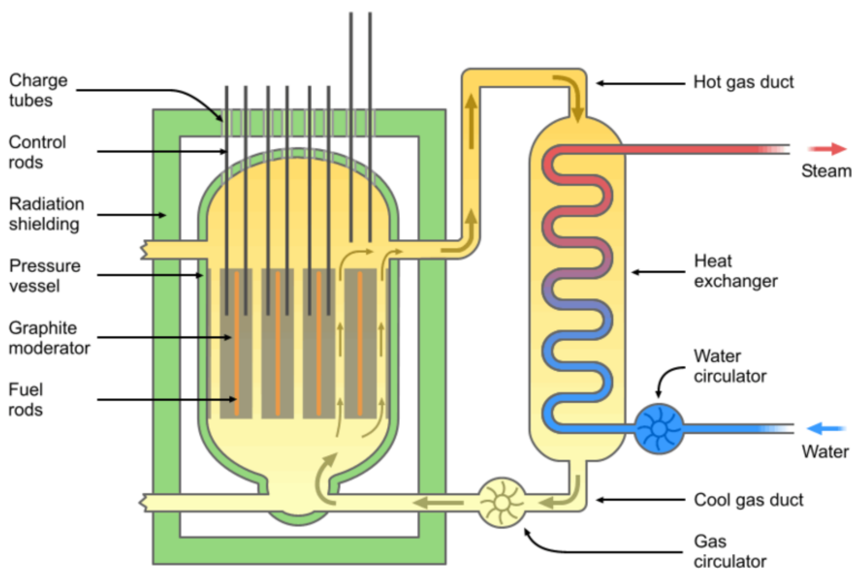
The masses of the reactants and products in arbitrary units are shown below the reaction. Notice that there is slightly less mass of the products than the mass of the reactants. The missing mass is converted into kinetic energy, contained mostly in the emitted neutron. Because of the $c^2 = (3x10^8\ m/s)^2 = 9x10^{16}\ m^2/s^2$ factor in Einstein's equation, a little mass converts into a large amount of energy.

36-3 The Nuclear Chain Reaction.—The key to releasing large amounts of energy from the nucleus is the achievement of a c**hain reaction** as illustrated on the right. The process starts with a single proton hitting a U-235 nucleus. This causes a fission reaction which releases 3 neutrons. These neutrons them hit more U-235 nuclei causing them to undergo fission, and so on. If the energy released in a chain



reaction is allowed to proceed in a **controlled** manner, this process can be used in a nuclear reactor to make electricity. The first controlled nuclear chain reaction was demonstrated by **Enrico Fermi** in 1942 in a laboratory under the stands of Stagg Field at the University of Chicago. If the chain reaction occurs in an **uncontrolled** manner, there is a sudden and catastrophic release of the nuclear energy --- this is a nuclear bomb.

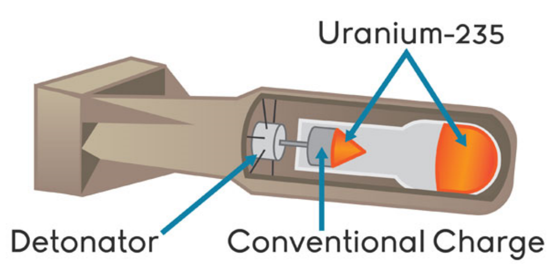
a. Nuclear reactors.—A nuclear reactor is a device containing a **fissionable** nuclear fuel, some type of **moderator** to control the chain reaction, and a **coolant** to absorb and carry off the heat produced by the process. The heat deposited in the coolant is used to make steam that turns the turbines of the electric generator. Nuclear reactor fuels are either U-235 or Pu-239, both of which are **fissionable materials – capable of undergoing nuclear fission**. The fuel is assembled into fuel rods about one cm in diameter and the rods are assembled into bundles of hundreds of individual rods. The stacks of fuel rod form the reactor core. A schematic of a reactor core is shown below.



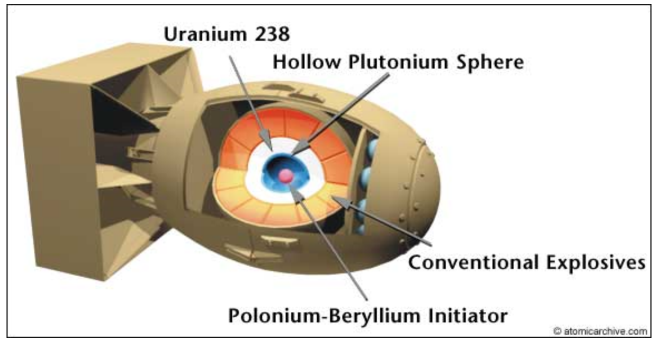
The fuel rods are embedded in a graphite moderator which slows down the fission neutrons to a speed where they are most efficient at causing fission. The reactions are controlled by control rods which are placed in-between the fuel rods. The control rods can be moved in and out of the core. The control rods are made of a material that is very good at absorbing neutrons. This is the key to controlled reactor operation. Some fission reactions occur spontaneously and produce neutrons that can initiate other fission reactions. The role of the control rods is to control the rate of neutron production. When the rods are in the core, fission reactions are suppressed. The startup of the reactor involves retraction of the control rods which then allows the neutrons from one fuel rod to go into an adjacent fuel rod and cause more fission events to occur. The reactor is operated in what is called the critical state in which each fission leads to only one more fission—a limited chain reaction. Under these conditions, the reactor produces a steady amount of electric power. The reactor can be turned off by inserting the fuel rods back into the core to absorb the neutrons and cut off the chain reaction.

Reactors are engineered to prevent going into a supercritical state in which chain reactions begin to produce an uncontrolled amount of energy causing the core to overheat and meltdown. The Chernobyl reactor went into a supercritical state, overheated and exploded with the release of radioactive material into the atmosphere. In most reactors around the world, the fuel is contained in a concrete and steel containment vessel which would prevent release of radioactive material in the event of a reactor malfunction. The Chernobyl reactor was not in a containment vessel. A list of the percentage of their power produced by various countries is shown on **slide 15**. Some of the pros and cons of nuclear energy are given on **slide 21**.

b. The atomic bomb.—Nuclear fission is a process typically referred to as **splitting the atom**. In fact, it is the nucleus that is split. **The atomic bomb utilizes nuclear fission as its energy source.** The first requirement for an atom bomb is to obtain a sufficient quantity of fissionable nuclear material. Ordinary uranium contains both U-238 and U-235, but only the U-235 is fissionable. The first step is uranium enrichment – separating the U-235 from the U-238. Weapons grade uranium requires enrichment to better than 20%. This is a complex process in itself that requires a long time period to accomplish. Also a critical mass of fissionable material must be present for a nuclear weapon. A small amount of enriched uranium does not produce enough neutrons to start a catastrophic chain reaction. To achieve critical mass (about 60 kg) two lumps of subcritical mass uranium must be quickly brought together. A schematic of a uranium-based atom bomb is shown on the right. The bomb is triggered by very quickly colliding two slugs of U-235 using a conventional explosive charge. The bomb explodes when the critical mass is formed. A



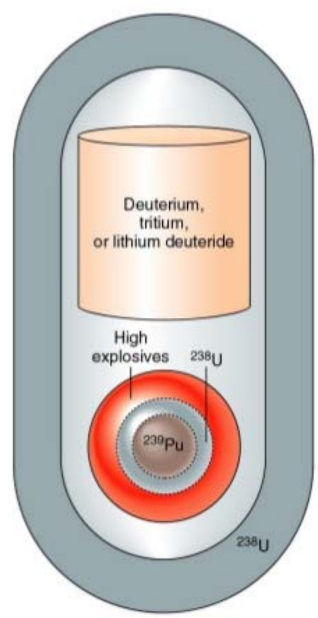
more complex process was used to detonate the uranium-plutonium bomb, as illustrated below. In this bomb, a shell of U-238 is arranged in a spherical configuration around a plutonium core. A conventional explosive shaped charged causes the uranium shell to implode onto the plutonium core producing a critical mass. This design is technically more complex, but the resulting weapon has a higher yield in terms of the equivalent amount of TNT. The yield of nuclear weapons is given by the amount of TNT that a conventional weapon would need to produce the same destructive effect. The first nuclear weapons had yields on the order of 16 kilotons, present-day weapons have yields in the megaton range.



36-4 Energy from Nuclear Fusion.—Energy is released in the fusion of deuterium (D) and tritium (T) forming an alpha particle $\left({}_{2}^{4}He\right)$ and one neutron.

Nuclear Fusion	${}_{1}^{2}D + {}_{1}^{3}T \rightarrow {}_{2}^{4}He + {}_{0}^{1}n.$

a. The hydrogen bomb.—The hydrogen bomb is powered by nuclear fusion of the two heavy isotopes of hydrogen, deuterium and tritium. The hydrogen bomb was based on the work of Edward Teller. The fusion process releases enormous quantities of energy. The H-bomb is actually a combined fission/fusion device. To fuse deuterium and tritium, they must collide with very high velocities. To achieve these high velocities, the deuterium and tritium must be heated to 100 million degrees C. The method of producing these conditions is illustrated in the diagram on the right. The bomb contains a vessel with the deuterium-tritium fusion fuel in close proximity to a conventional uranium-plutonium fission bomb. The energy released by the atomic bomb heats the deuterium-tritium mixture to thermonuclear temperatures so that the fusion process occurs releasing



neutrons which then continue to drive the fission chain reactions. The yields of an H-bomb are in the range of several megatons. The Soviet Union in 1961 detonated an H bomb that had a yield of 50 megatons.

b. *Controlled thermonuclear fusion.*—The possibility of using a nuclear fusion based device as a controlled energy source (**fusion reactor**) has been investigated worldwide for since the early 1950s. The principle is to create the proper conditions of temperature and density in a gas of tritium so that fusion reactions occur and the energy released can be harnessed to produce electricity. This requires a gas at temperatures comparable to those in the Sun. Such a hot gas obviously cannot be contained in any conventional vessel. Since the hot gas contains charged particles, the idea is to confine it using magnetic fields. This has proven to be a very difficult problem to solve, and has not yet been achieved, although significant progress has occurred. Tritium can be produced from deuterium and deuterium accounts for approximately 0.0156% of all the naturally occurring hydrogen in the oceans. Thus the fuel supply is essentially limitless.

A collaborative project involving the EU, US, India, Japan, Russia, South Korea, and China is currently under construction in Cadarache, France to build a device (**ITER**) which will demonstrate the feasibility of producing energy from nuclear fusion. The schematic of ITER is shown on the right. For scale, a person is standing in the lower right corner (red circle). If successful, fusion reactors may be the leading source of electric power for the future. A fusion reactor does not produce harmful emissions, and it is not subject to the catastrophic accidents that can occur in fission reactors.