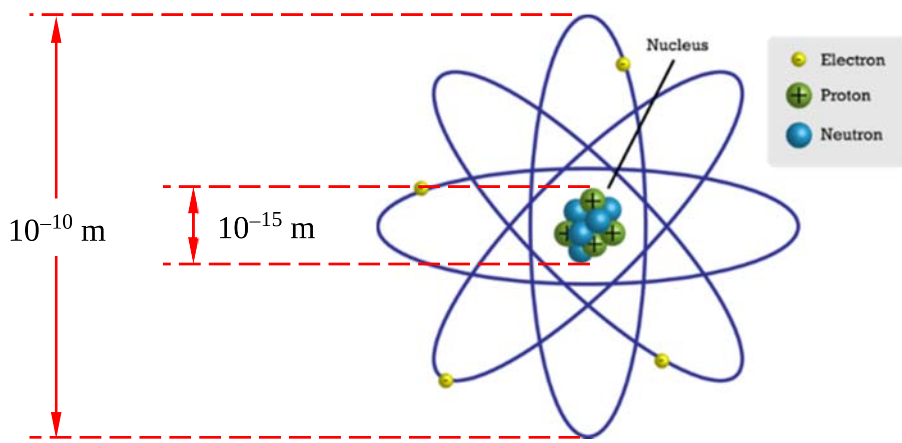
PHYS:1200 LECTURE 35 — ATOMIC AND NUCLEAR PHYSICS (3)

The first two lectures in this unit dealt with atomic physics – and the new physics (Quantum Mechanics) that was developed to understand the behavior of the electrons in atoms. Quantum Mechanics replaces Newton's mechanics as the proper framework for understanding atomic-scale phenomena. The application of the classical laws which were developed based on observations of macroscopic objects does not work in the atomic world. In the next two lectures we will go deeper into the atom to explore the **nucleus**. We will consider the structure of the nucleus, the forces that hold it together, radioactivity, and the processes that release enormous amounts of energy either in a controlled manner (nuclear reactor) or in an uncontrolled manner (nuclear weapon).

35-1. The Atomic Nucleus.—The nucleus is the core of the atom and contains more than 99.9% of the mass of the atom. The standard picture of an atom (beryllium) is shown below. This picture misleading because it is not to scale. The nucleus is roughly 100,000 times smaller than the atom.



a. The nuclear particles.—The nucleus contains two types of particles: **protons and neutrons**. Protons are positively charged and the attractive electric force between the protons in the nucleus and the electrons binds the atom together. Under normal conditions of electrical neutrality, the number of protons in the nucleus is equal to the number of electrons in the atom. If one or more electrons are removed from the atom, the resulting object has a net positive charge and is referred to as an ion.

Protons have a charge of +e, and **neutrons** have no charge, 0e (e is the basic unit of electric charge, the electron charge is –e). The mass of the neutron and proton are approximately the same, and roughly 2000 times the mass of the electron. Thus, the nucleus accounts for most of the atom's mass as noted above. The electron, proton, and neutron are three of the fundamental particles of nature from which all matter is formed.

b. Terminology and notation of nuclear physics.—There are three parameters used to characterize the nucleus: atomic number (**Z**), neutron number (**N**), and atomic mass number (**A**). The **atomic number Z** is the number of protons in the nucleus. An electrically neutral atom has Z electrons. The atomic number Z identifies a particular atom. Hydrogen has one proton, Helium has 2 protons, Lithium has 3 protons, Uranium has 92 protons, etc. The **neutron number N** is the number of neutrons in the nucleus. An atom (identified by its Z) can have forms that contain different numbers of neutrons in the nucleus. Nuclei with the same Z but different N's are called isotopes. The **atomic mass number A** is the number of protons and neutrons, so that

Atomic mass number	$A = Z + N$	[1]

The mass of the nuclei (and the atom) is proportional to A. For example, a helium atom has a nucleus containing two protons and two neutrons, so that Z = 2, N = 2, and A = 4. Nuclei are designated using the following notation:

Nuclear notation	${}^{A}_{Z}X,\ \ A = Z + N$	[2]

Where X is the usual symbol for the element. The number of neutrons in the nucleus is then N = A – Z. The nucleus of hydrogen contains one proton and no neutrons and is designated ${}^{1}_{1}H$.

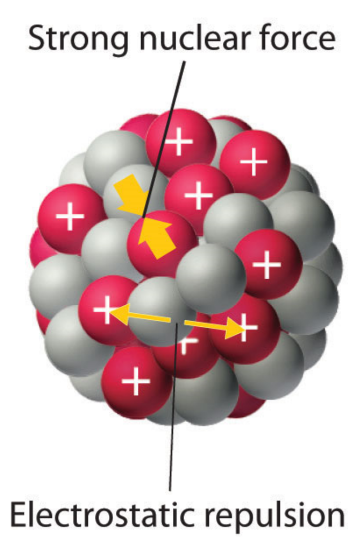
EXAMPLE 35-1: What is the number of protons and neutrons in cobalt-60 $\left({}^{60}_{27}Co\right)$?

Solution- # protons = Z = 27, # neutrons = N = A – Z = 60 – 27 = 33.

c. Isotopes.—Many elements have multiple **isotopes** – nuclei with the same number of protons (Z) but different numbers of neutrons (N). For example, hydrogen has two isotopes: **deuterium** which has one proton and one neutron and is designated as ${}^{2}_{1}H$, and **tritium** which has one proton and two neutrons and is designated as ${}^{3}_{1}H$. These three atoms are all hydrogen in the sense that they behave chemically in a similar manner, since chemical reactions involve only the electrons, and all three species of hydrogen have one electron. The table below lists further examples of isotopes. Uranium-238 is the naturally occurring isotope. Uranium-235 is enriched uranium and is the isotope needed to produce nuclear weapons. Radon is a radioactive gas that occurs naturally in the earth. The by-products of its radioactivity are a cancer hazard, and it is the second most prevalent cause of lung cancer.

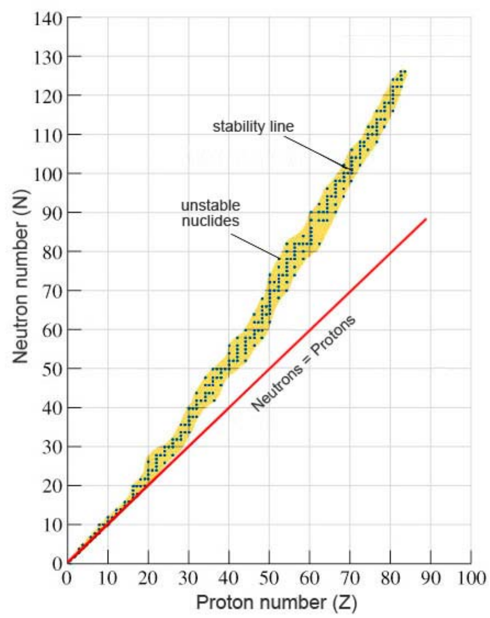
SPECIES	SYMBOL	NUCLEAR CONSTITUENTS
Helium-3 Helium-4	${}^{4}_{2}He$ ${}^{3}_{2}He$	2 protons, 2 neutrons 2 protons, 1 neutron
Carbon-12 Carbon-13 Carbon-14	${}^{12}_{6}C$ ${}^{13}_{6}C$ ${}^{14}_{6}C$	6 protons, 6 neutrons 6 protons, 7 neutrons 6 protons, 8 neutrons
Radon-222	${}^{222}_{88}Ra$	88 protons, 134 neutrons
Uranium-235 Uranium-238	${}^{235}_{92}U$ ${}^{238}_{92}U$	92 protons, 143 neutrons 92 protons, 146 neutrons

35-2 The Nuclear Force.—The nucleus contains positively charged protons contained in a very small volume. Obviously, since the protons experience a repulsive electric force, some other **attractive force** must also be present to hold the nucleus together. This force is called the **nuclear force** (or strong nuclear force). The nuclear force is one of the fundamental forces of nature. The nuclear force is an attractive force between protons and neutrons, protons and protons, and neutrons and neutrons. The nuclear force is a short-range force – it is only effective



when the particles are very close together, and it does not extend beyond the nucleus.

The role of the neutrons in the nucleus is to provide more of the nuclear force to confine the protons, without adding any electric repulsion. For elements with Z less than about 20, the number of neutrons is close to the number of protons. However, as we go up the periodic table of the elements to higher and higher values, the number of neutrons in the nucleus increases significantly. Notice that in the table above, the number of neutrons in U-238 is 146, 54 more neutrons than protons. This trend is illustrated in the graph on the right. The red line indicates the case Z = N. **The stable nuclei (the ones that do not disintegrate) for Z > 50 have many more neutrons than protons.**



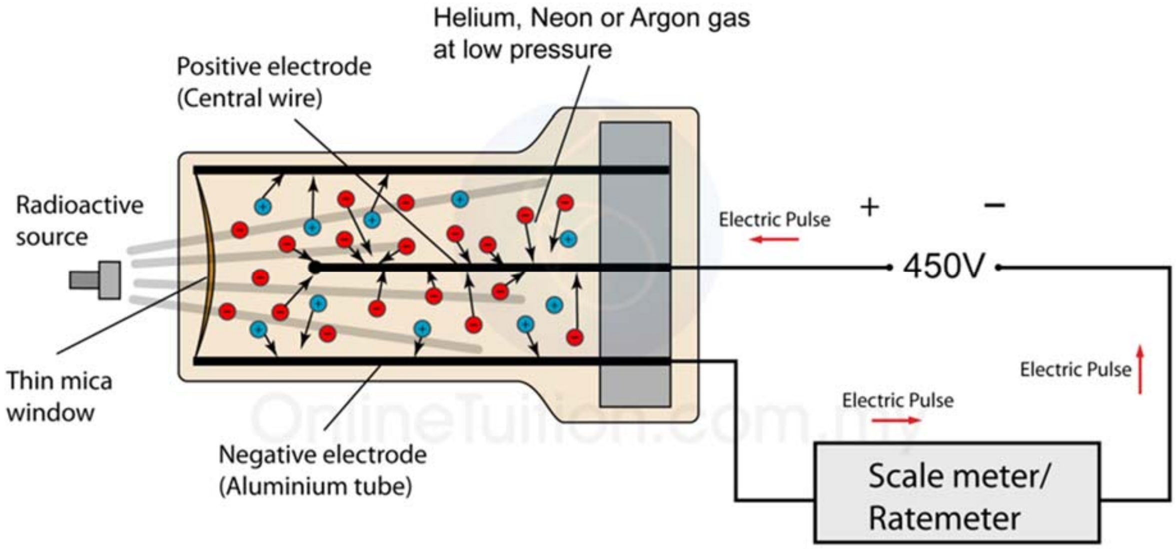
35-3 Unstable Nuclei.—In some nuclei, the balance between electrostatic repulsion between the protons which acts to blow the nucleus apart, and the nuclear force which holds it together is very delicate. Some nuclei are always just on the verge of breaking up and spontaneously emits particles or photons (gamma rays) at random times in an attempt to achieve more stability. This phenomenon is called **natural radioactivity** --- the emission of radiation by an unstable nucleus. An unstable nucleus can disintegrate by the emission of particles or gamma ray photons.

a. Radioactivity.— Any of three particles, $\alpha 's, \beta 's, or\ \gamma 's$ are emitted by an unstable nuclei:

1. alpha ray emission
2. beta ray emission, and
3. gamma ray emission.

Alpha particles are a composite of 2 protons and 2 neutrons --- a helium nucleus $\alpha = {}^{4}_{2}He.$ The nucleus of He is a very stable nucleus. Beta particles are just electrons. The electrons are not in the nucleus, but are produced in a process called **beta decay** in which a neutron decays into a proton and an electron. The gammas are just very energetic photons. The $\alpha 's$ and $\beta 's$ are charged particles and the $\gamma's$ have no charge. The $\alpha's$ have a charge of +2e, and the $\beta's$ have a charge of –e. Since the $\alpha's$ and $\beta's$ are charged, they can be deflected by a magnetic field, while the $\gamma's$ are not affected by a magnetic field. Thus magnetic fields can be used to determine which particle is emitted by a particular unstable nucleus (**slide 15**).

b. The Geiger counter.—The **Geiger counter** (right) is an electronic device that detects the presence of radioactivity. The detecting element of a Geiger counter is a Geiger-Muller (**GM**) tube shown schematically below. A GM tube is a closed metal cylinder that is filled with an inert gas at a pressure of roughly one-tenth of atmospheric pressure. (see schematic below) One end of the tube has a thin window typically made of mica. A thin wire is positioned along the axis of the tube and is insulated from the tube itself and biased to a large positive voltage relative to the walls. The principle of operation of a GM tube is based on



ionization of the inert gas atoms by alpha, beta, or gamma particles that enter the thin mica window. When one of these particles enters the tube, it is energetic enough to knock electrons out of the inert gas atoms (ionization). The liberated electrons migrate to the positive center wire acquiring energy as they move toward it. As a result, the liberated electrons can ionize more atoms. Liberating even more electrons which can also ionize. As a result, an avalanche of liberated electrons is formed which are collected by the center wire producing a pulse of current which is detected by the electronic circuit. Often, the current pulse is used to produce a sound pulse known as a blip. Monitoring the blip rate provides a qualitative indication of the presence of radioactivity.

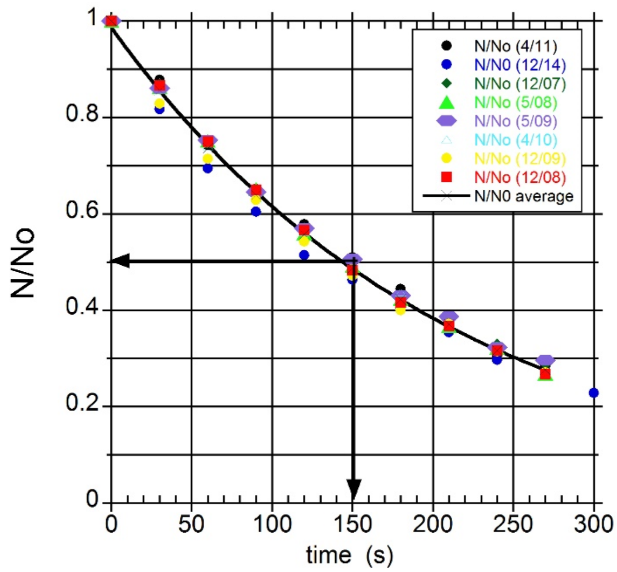
c. Half-life of a radioactive substance.—Half-life is used to quantify radioactive decay. **One half-life, designated $T_{1/2}$, us the time it takes for one half of the nuclei of a sample of a given radioactive isotope to decay.** Every isotope has its own characteristic half-life. Radioactive decay is a random process. This means, that if we have a sample that contains, say 1 million radioactive nuclei, any one of them can decay (emit an $\alpha,\ \beta,\ or\ \ \gamma$) at any time. If the radioactive isotopes in this sample have a half-life of 1 day, then after one day, on average, 500,000 would have decayed. We cannot predict when a particular nuclei will decay, but in a sample containing a large number of them, we can expect half of them to decay in one half-life. The half-lives of radioactive nuclei vary greatly from fractions of a second to thousands of years. For example $^{8}_{2}Be$ has a half-life of $1\times10^{-16}s$, while $^{238}_{92}U$ has a half-life of 4.5 billion years.

EXAMPLE 35-2: A sample contains 10,000 nuclei of radioactive $^{131}_{53}I$. If the half-life of the radioactive isotope is 8 days, how many radioactive nuclei will remain in the sample after 32 days?

Solution-

Number	time (days)
10,000	0
5000	8
2500	16
1250	24
625	32

625 radioactive nuclei will remain after 32 days.



Radioactive decay and half-life will be demonstrated in class. A sample of a radioactive nuclei will be activated chemically and then its activity (the number of decays per second) will be monitored with a GM tube and an electronic device. The results of this experiment performed each semester for a number of years is shown on the right. Since the number radioactive nuclei initially in the sample differs each time the measurement is made, the data from each measurement is normalized to its initial value so they can be shown on one plot. The half-life is determined by the time when the normalized number $N/N_0 = 0.5$; in this case, $T_{1/2} = 150$ s.

d. Nuclear reactions.—When a nuclei decays by the emission of an alpha or beta particle, the number of protons changes so the nuclei is transformed into another element. This process is called **nuclear transmutation.** For example, Radon-222 decays by the emission of an alpha particle (He nucleus) in the nuclear reaction

$$^{222}_{86}Ra \rightarrow {}^{218}_{84}Po + {}^{4}_{2}He.$$

Since an alpha particle contains 2 protons and 2 neutrons, the number of protons decreases by 2, the number of neutrons decreases by 2, and the atomic mass number A decreases by 4. Since the Z is changed to 84, the resulting nucleus is no longer radon but is transformed into polonium which has 86 protons.

Beta decay is the emission of an electron by a radioactive nuclei. In beta decay, a neutron in the nucleus decays into a proton and an electron. The proton remains and the electron is ejected, typically with a lot of kinetic energy. Beta decay is symbolically represented by the reaction

BETA DECAY	${}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-}.$

Notice, that charged is conserved (as it always is) in this reaction. Carbon-16 decays by beta decay in the reaction

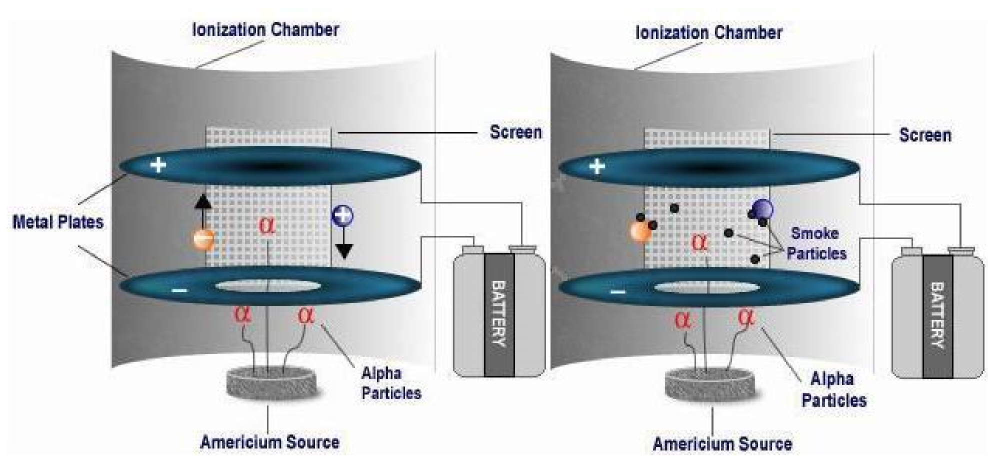
$$ {}^{16}_{6}C \rightarrow {}^{16}_{7}N + e^{-}. $$

The product of beta decay contains one more proton, so the Z is increased by 1, but the A remains the same because a neutron was swapped for a proton. Since Z changes, the nuclei is a different atom, in this case a nitrogen atom.

Some radioactive nuclei decay by the emission of a gamma ray (energetic photon). For example Cs-137 undergoes beta decay to Ba-137 (half-life 30 years) which then emits energetic gamma rays. Since no protons are involved, it remains as Ba when gammas are emitted.

e. Applications of radioactivity.—**Carbon dating** is based on the radioactive decay of C-14. Carbon is a constituent of all living organisms and they contain both C-12 and C-14. C-14 decays with a half-life of 5700 years and C-12 does not decay—it is stable. Thus the ratio of C-12 to C-14 in an organism depends on the age of that organism. By measuring this ratio, it is possible to estimate its age.

Smoke detectors use radioactivity to detect the presence of smoke particles. A schematic diagram of a smoke detector is shown below. Smoke detectors contain a sample of a radioactive



material that emits alpha particles. The alpha particles knock electrons off of air molecules which then flow to a positive plate creating a small current that is detected by an electronic circuit. When smoke particles enter the region between the two plates some of the ions attach to them, and this disrupts the flow of current. When the electronic circuit senses a drop in current it sets off the alarm. Some fluorescent lights also use an alpha source to initiate the ionization of the gas in the tube. Although they are no longer available, wristwatches used to have luminous hands and numerals, because the paint used had a small amount of radium in it that glowed in the dark.

Radioactive nuclei are used in **medical applications** to kill cancer cells. Small amounts of radioactive materials can be embedded in tumors. The particles emitted by the radioactive nuclei embed themselves in and kill cancerous cells. To prevent long term exposure to radioactive materials embedded in the body, radioactive materials with short half-lives and high activity levels are used. Such radioactive samples can be produced by a process called **nuclear activation**. When a stable nuclei is bombarded by neutrons or protons it can transformed into a radioactive nuclei having a short half-life. A sample can be activated by exposing it to neutrons from a nuclear reactor. Some medical facilities (including the UIHC) have in-house devices to accelerate protons and produce activated samples for cancer treatment.