Radiation Fundamentals for Radon Professionals

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Introduction

Although radon testers, mitigators and laboratories deal with radiation as part of their everyday experience, few radon professionals have had more than a brief introduction to radiation in a formal setting. The purpose of this workshop is to augment this prior training, starting with an introduction to the three types of radiation encountered in the radon field and ending with some practical experiments using a Geiger counter, with an emphasis on using a Geiger counter as an augment for a radon business.

Ionizing Radiation

The word radiation has several different meanings in physics. Visible light, for example, is properly called radiation in science. Visible light simply happens to be a small part of the electromagnetic spectrum that includes radio waves, television signals, microwaves, infrared, ultraviolet light, x-rays and gamma rays, all of which are examples of electromagnetic radiation. Another use of the word radiation comes to us from the world of the atom. At the atomic level, radiation can refer to particles or energy which are emitted from within the atomic nucleus, energy from the electrons orbiting the nucleus (x-rays) or even fast moving atom-sized particles shot out from a reactor, the sun, or far away galaxies (protons, for example, which travel intergalactic distances and are called primary cosmic rays).

In this presentation, however, we will focus on a particular type of radiation that is encountered by radon professionals. This is the radiation that is emitted from the nuclei of radon and the radon decay products. This radiation comes under the broad category of ionizing radiation. It is identified as ionizing simply because that’s what it does; it ionizes many of the atoms that the radiation encounters.

What is Ionization?

Matter is made up of atoms which, in turn, are made up of a nucleus that is normally surrounded by a cloud of electrons. In figure 1, below, a nucleus, made up of four protons (light gray) and five neutrons (dark gray), is surrounded by four electrons. The paths of the rapidly moving electrons are shown as two dotted ovals, two electrons on each path.

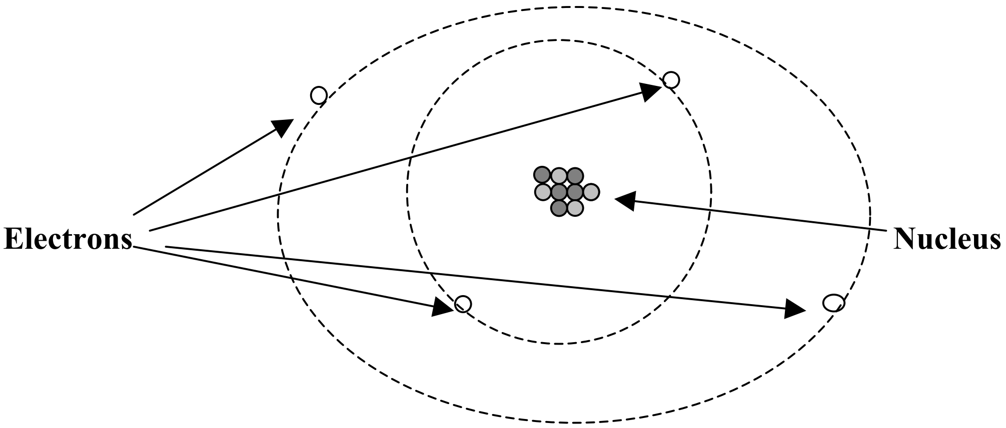

Figure 1: A simple model of an atom showing a nucleus and four electrons. The electrons are moving in two orbits, shown as dotted lines.

In the picture above, notice that there are four electrons orbiting the nucleus and four protons (light gray circles) within the nucleus. In everyday life, as in this example, the number of electrons normally equals the number of protons. Since electrons each carry a unit negative charge and protons carry a charge equal in magnitude but of the opposite sign (positive), atoms typically have no net charge as the charge on the protons equals, and cancels out, the negative charge of the electrons.

It is not difficult to disturb this fine balance, however, as electrons can easily be removed, or added, to an otherwise neutral atom. In the radiation story, as we are discussing here, electrons are removed from the atom by radiation which is passing close to the electron orbits. Once an electron is removed, the atom is referred to as an "ion", and the process of removal of the electron is called "ionization". See figure 2, below.

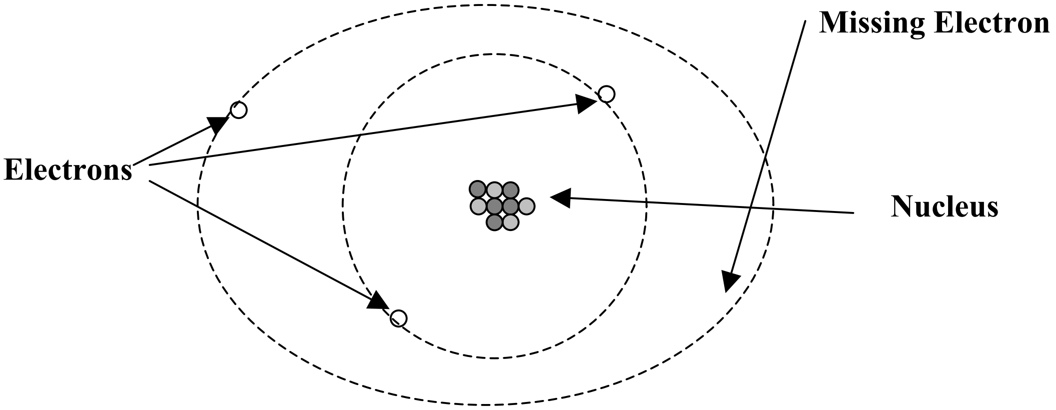

Figure 2: An atom, now an ion, missing one electron

So, we are now able to fully define what is meant by ionizing radiation: **ionizing radiation is any particle or energy packet that, when it passes close to an orbital electron, removes the electron, leaving an ionized atom behind.**

Different physics textbooks can't seem to agree on which radiation is to be called "ionizing radiation", but all textbooks agree that alpha and beta particles (from the nucleus of a radioactive atom) are ionizing radiation and some textbooks call gamma radiation (a packet of energy from the nucleus of a radioactive atom) ionizing radiation. **For the purposes of this presentation, we will call alpha, beta and gamma all ionizing radiation** although the amount of ionization per unit length of material is much less for gamma than it is for alpha and beta as they travel through the material.

By contrast, visible light, microwaves, infra-red and ultraviolet light, radio waves, and television signals are not ionizing radiation because they do not carry enough energy to remove the electron from its orbit. Neutrons, which actually can be isolated and "shot" at atoms, are not normally considered ionizing radiation either because they have no net charge (1). As a result, there is no way for a neutron to interact with an electron (2).

For completeness, here is a brief list of other ionizing radiation descriptions, although they will not be further discussed because they are not encountered in the radon story: protons, primary cosmic rays (protons), secondary cosmic rays (muons), x-rays and positrons.

Why Is Ionization Important?

Ionization is important to radon professionals for three reasons. First, ionization is most certainly the process that occurs when radiation strikes the human body. In particular, when radiation from radon and the radon decay products strikes the lung cells, the atoms of the DNA of the lung cells are ionized. This leads to a change in the chemistry and the charge of the atoms within the DNA. As a result, the DNA no longer behaves in the way that normal DNA behaves, which can, in turn, lead to lung cancer (3).

Second, the units of radiation exposure are expressed in terms of the ionization that is caused by that radiation. To understand this definition, imagine that there is a cubic centimeter of dry air under standard conditions (1 cm^3, 0^o C, at 760 mm Hg). Now, allow a sufficient flux of X-rays or gamma rays to pass through the dry air so that enough ionization takes place such that the totality of the freed electrons (or, equally, the positive air ions) within this cubic centimeter of air have a charge of one electrostatic unit (1 esu), where each single freed electron contributes 4.80×10^{-10} electrostatic units to this total.

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(1) *See one author's delineation between ionizing and non-ionizing radiation in the well-known text: Introduction to Atomic and Nuclear Physics, 3rd Edition, Oldenberg, O., McGraw-Hill, 1961, page 275. For a second, opinion, see Nuclear Radiation Physics-3rd Edition, Lapp, R. and Andrews, H., Prentice-Hall, 1963, page 273. Both of these authors discuss neutron interactions in some detail.*

(2) *Neutrons can, however, be absorbed by the nuclei of other atoms. The atom subsequently may release gamma rays (capture gamma rays), which can interact with electrons. Also, free neutrons can spontaneously change into protons and electrons, both of which are ionizing radiation. Strictly speaking, then, it is not the neutron which does the ionizing, but the products of the neutron's interaction with other atoms or its disintegration which does the ionizing. Hence, we, and the authors of most textbooks on nuclear reactions, will call the neutron itself a non-ionizing radiation particle.*

(3) *There are many good books and articles about how radiation interacts with the human body but it so happens that Nuclear Radiation Physics-3rd Edition (mentioned above) does a good job of it on pages 383 ff.*

This amount of X-rays or gamma rays, that causes this much ionization is defined to be one roentgen, and is abbreviated as a capital R. Since most of us do not have an intuitive feel for the electrostatic unit of charge, it should be mentioned that 1 esu accumulates when 2.083 X 10^9 electrons are freed within this cubic centimeter of air. That is, one roentgen of radiation exposure ionizes more than 2 billion air atoms in each cubic centimeter of air. That's a lot of ionization.

Please notice that we are talking about radiation exposure here, i.e.; how much radiation is in the area. We are not talking about the activity or concentration of radioactive atoms, but about how much radiation is produced by these radioactive atoms. If we want to measure the *concentration* say, of radon, that unit (as you all well know) is the curie. One curie equals the concentration of radioactive atoms that are undergoing 3 X 10^{10} disintegrations each second (or 2.2 disintegrations per minute if you are talking about a picocurie).

Third, several radiation measurement devices work by monitoring the amount of ionization occurring inside of a small chamber. The Eperm™, a very popular passive radon measurement device, measures radon by "recording" the number of electrons freed from the air within the ion chamber (the interior of the device) by the ionization of that air by alpha, beta and gamma radiation released within the chamber from radon and its decay products. Another device, a continuous monitor manufactured by *femto*-Tech™, "counts" the alpha particles from radon and its decay products as the alpha particles ionize the air between two charged screens within the monitor. The Geiger counter, another well-known radiation device, actually has a small tube within which the ionization takes place. The sealed tube is filled with an inert gas, usually argon, that is ionized by beta, gamma and, for tubes with a special mica window, alpha. Although Geiger counters can not be used to measure radon because they are sealed, they are useful adjuncts to a radon measurement device for reasons that will be explained later in this presentation.

So, in conclusion, we want to understand ionization better because it (1) helps us understand the interaction of radiation with the human body, (2) it helps us understand where the unit of radiation exposure comes from (the roentgen) and (3) it helps us better understand how a Geiger counter works.

Isotopes

As mentioned earlier, we will only discuss three types of ionizing radiation in any detail in this presentation: the alpha particle, the beta particle and the gamma ray.

In order to understand why radiation is emitted from the nucleus of an atom, it is necessary to return to the simple model of the atom that we saw earlier. Only, this time we will concentrate on the nucleus of the atom rather than the orbital electrons. In the diagram below, notice that the neutrons and protons are equal in number in the nucleus of this beryllium atom.

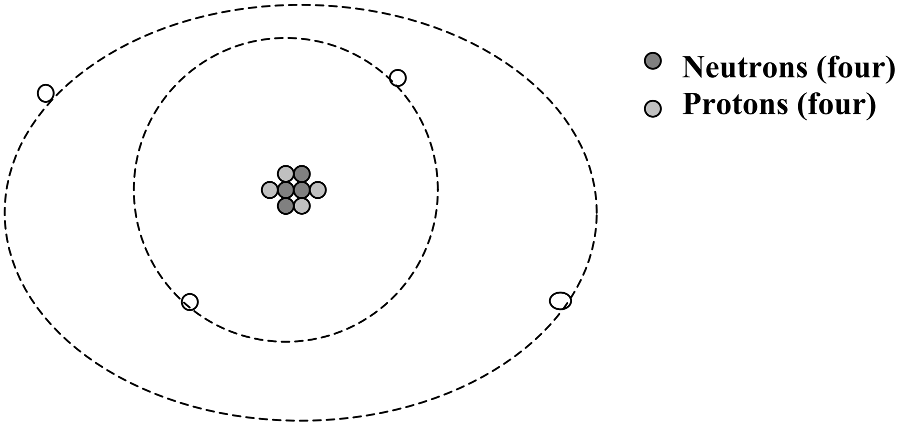

Figure 3: A beryllium atom, showing the four neutrons and four protons within the nucleus.

This is not always the case, however, as nature provides us with many varieties of atoms and for many of these atoms the number of neutrons is not the same as the number of protons. Thus it is possible to have atoms with 4 protons and 4 neutrons, as in our example above, but it is also possible to have atoms with 4 protons and 5 neutrons. Or, it is possible to have 4 protons and 6 neutrons. Any atoms that have the same number of protons but differing number of neutrons, as in these three examples, are called isotopes of each other. Using the total number of nucleons (number of protons plus number of neutrons) as a label, we can name the various isotopes of beryllium as beryllium-8, beryllium-9 and beryllium-10 (4). See the figure 4 below:

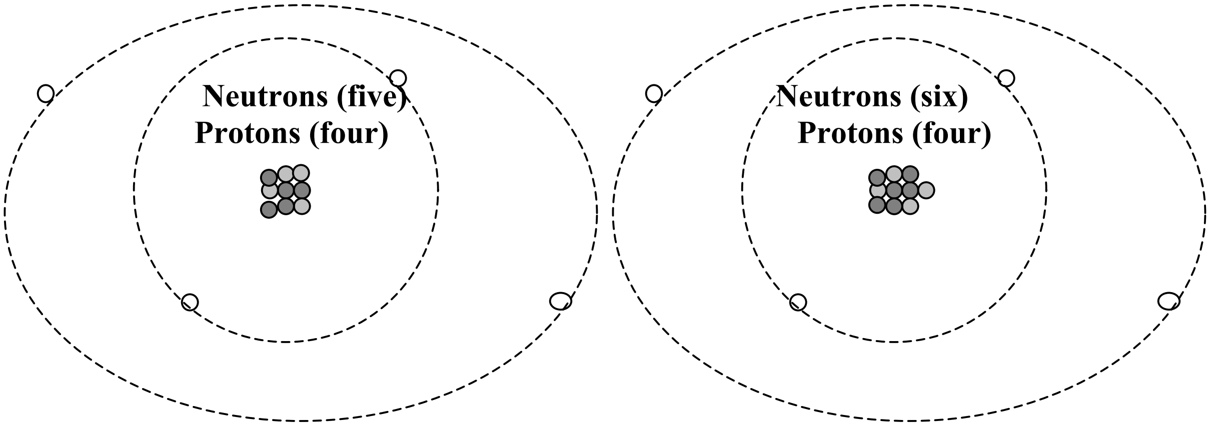

Figure 4: A beryllium-9 atom on the left has 4 protons and 5 neutrons. The beryllium-10 atom on the right has 4 protons and 6 neutrons. The third isotope of beryllium, beryllium-8 is shown above in figure 3.

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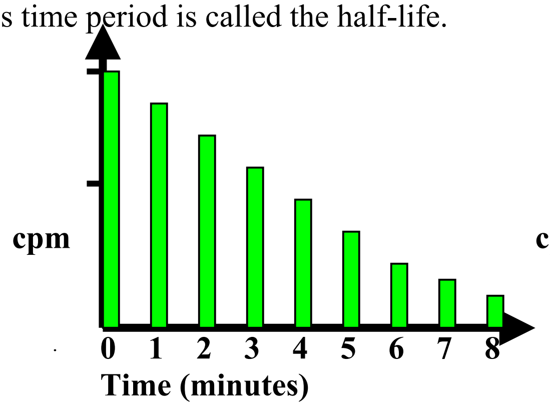
(4) For a list of isotopes of various atoms, see Radioactive Decay Data Tables, A Handbook of Decay Data for Application to Radiation Dosimetry and Radiological Assessment, Kocher, David C., Technical Information Center, U.S. Department of Energy, 1981. Beryllium-9 is the only stable (non-radioactive) isotope of five isotopes of Beryllium.

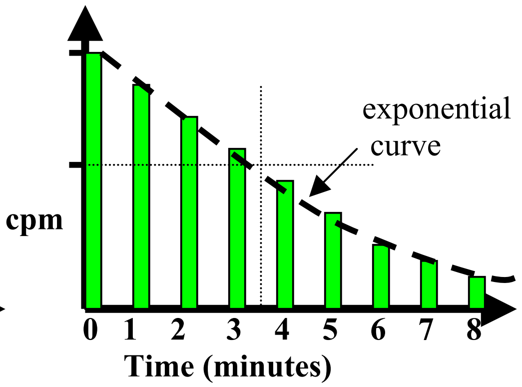
In summary, all atoms come in different varieties, called isotopes. An isotope is the relationship among various atoms that have the same number of protons but differing number of neutrons. An isotope is labeled by its name (for example, beryllium) and its **mass number** (the number of protons plus the number of neutrons). Each element has its own distinct number of protons. For example, all isotopes of hydrogen have one proton. All isotopes of helium have two protons. All isotopes of lithium have 3 protons, and so on through the periodic table. Later in this presentation, we will be talking about radon (with 86 protons), lead (with 82 protons), bismuth (with 83 protons) and polonium (with 84 protons). For convenience, we will call the **number of protons the atomic number** so that we can say, for example, that the atomic number of radon is 86. Each element has a unique atomic number, which can be found on any periodic table.

Half-Life

Radiation is the by-product of an isotope changing into another isotope. One convenient way of measuring how fast an isotope does this radioactive changing is called the half-life. Because radioactive changing, or radioactive decay, is properly described using statistics, the half-life is best thought of as the time it takes for a half of a large group of similar isotopes to radioactively decay. Isotopes, in a sense, are like people. You can't predict precisely when any one person will die, for example. You can, however, predict the average age of death for a large group of people. In a like manner, you can not predict when one isotope will radioactively decay, but you can predict, with great certainty, the average time that it will take for a large group of similar isotopes to decay. Instead of the average life, however, the half-life is commonly used in radiation.

The half-life for many isotopes is easily determined by experiment. One simply gathers a large number of identical isotopes and measures the amount of radiation, in counts per minute, using, say, a Geiger counter. A short time later, the amount of radiation is measured again. After repeated measurements, a graph can be made. Then, examination of the graph reveals how much time passed until the amount of radiation dropped in half. This time period is called the half-life.





On the left, a graph has been constructed which records the counts per minute found each minute, using a Geiger counter. Notice, on the graph on the right, that it was determined that the counts per minute have dropped to half of its original value at around 3 ½ minutes. Also shown on the right is a dashed curved line that represents the half-life curve, called an exponential curve, for this particular (made up) isotope. Thus, the half-life for this isotope is 3 ½ minutes. The half-life for other isotopes can range from a fraction of a second to billions of years. Radon-222, for example, has a 3.8 day half-life.

Why Radiation Occurs

The three types of radiation discussed in this presentation, alpha particles, beta particles and gamma rays all initiate in the nucleus of a radioactive isotope that either has too many neutrons or too few neutrons in its nucleus.

You see, the nucleus can be thought of as a complex tug-of-war going on between the protons and the neutrons. The protons, because of their respective positive charges, are all trying to repel each other. The neutrons, on the other hand, act as the “glue” holding the protons together. Surprisingly, the number of neutrons required to balance out the effect of the charge repulsion on the protons is not necessarily equal to the number of protons. That is, except for the very lightest atoms, the number of neutrons does not equal the number of protons. This is especially true as one moves through the periodic table past atoms with 40 protons and beyond (zirconium and heavier). For most atoms, the number of neutrons required to offset the positive repulsion is greater than the number of protons because the “extra” neutrons are required to shield each proton from every other proton. In fact, the example we have been using throughout this presentation, beryllium, requires 5 neutrons to offset the repulsive effect of its 4 protons. (See table 1, below).

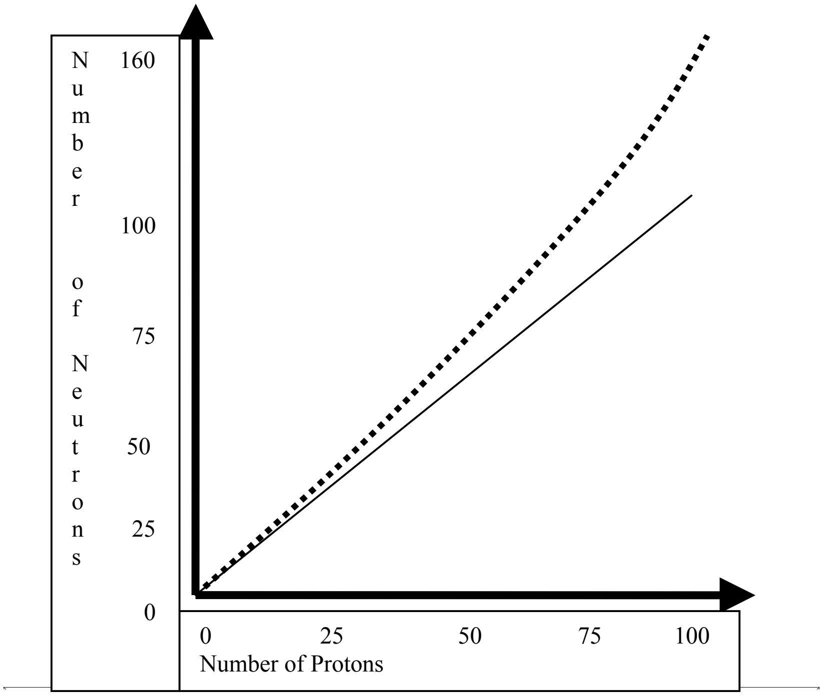


Table 1: The straight line, going 45^0 up and to the right, shows a theoretical line of equal number of neutrons and protons. In actuality, however, the number of neutrons exceeds the number of protons, as shown by the dashed “stability line”.

We are now ready to understand how radiation occurs. Atoms that have too many neutrons have too much "glue". Such atoms will spontaneously change in order to correct the situation. They do so by getting rid of one neutron in their nucleus. The process is a little more complicated than that, however, because it gets rid of this extra neutron by first changing the neutron into a proton and an electron, and then emitting the electron at 99 % of the speed of light. These electrons are called **beta particles**. As a result of beta particle production, the nucleus has now changed. It now has one less neutron and one more proton than it did earlier. Since the new nucleus has one more proton than the original nucleus, the identity of the atom has also changed. By counting the new number of nucleons, one can see that its mass number has not changed; although the number of protons has increased by one, the number of neutrons had decreased by one, leaving the mass number the same. In summary, a beta particle is released when the nucleus has too many neutrons. As a result of this release, the atomic number of the isotope increases by one (the element becomes a new element) and the mass number stays the same.

On Table 2, below, the small circle represents the mapping of some isotope on the neutron/proton chart. This isotope evidently has more neutrons than is necessary for nuclear stability because it is located above the dashed line of stability (more neutrons causes its position to be higher, for any given number of protons). The isotope will attempt to become stable by emitting a beta particle, moving the isotope's position down (one less neutron) and to the right (one more proton).

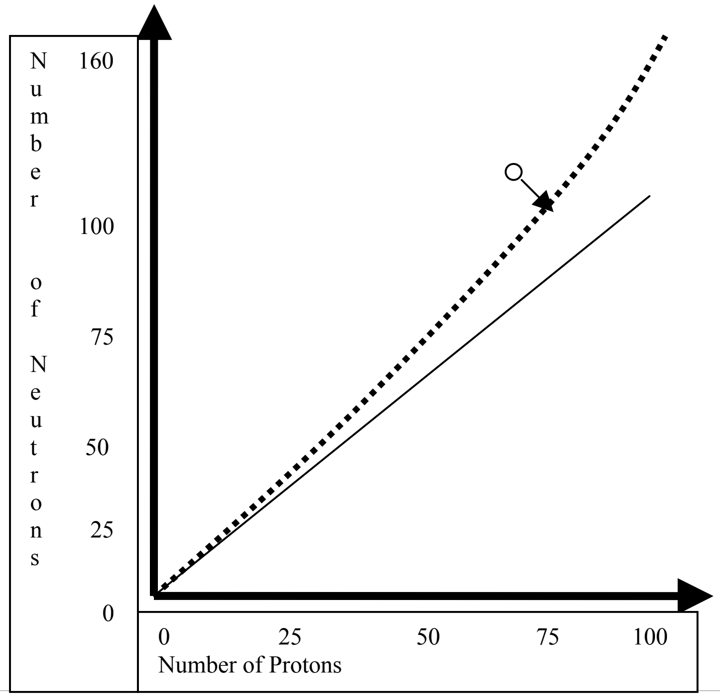


Table 2: An isotope with too many neutrons is always shown above the curved line of stability. Beta decay causes the nucleus to lose one neutron and gain one proton, moving the location of the isotope down, and to the right, towards the line of stability.

Alpha particles are emitted when the nucleus has fewer neutrons than necessary to hold the nucleus together. When there are too few neutrons, there is not enough "glue" to hold the nucleus together. Nature tries to correct this situation by spontaneously emitting 2 neutrons and 2 protons (all stuck together) at about 90 % of the speed of light.
An alpha particle is nothing more than 2 neutrons and 2 protons, all clumped together. Any isotope that has too few neutrons will be graphed below the line of stability on the neutron/proton chart. This is because the fewer number of neutrons will position the isotope lower on the chart because it has fewer neutrons for a given number of protons. The release of an alpha particle will result in a more stable isotope because it moves the position of the isotope down, and to the left, approaching the stability line. See Table 3.

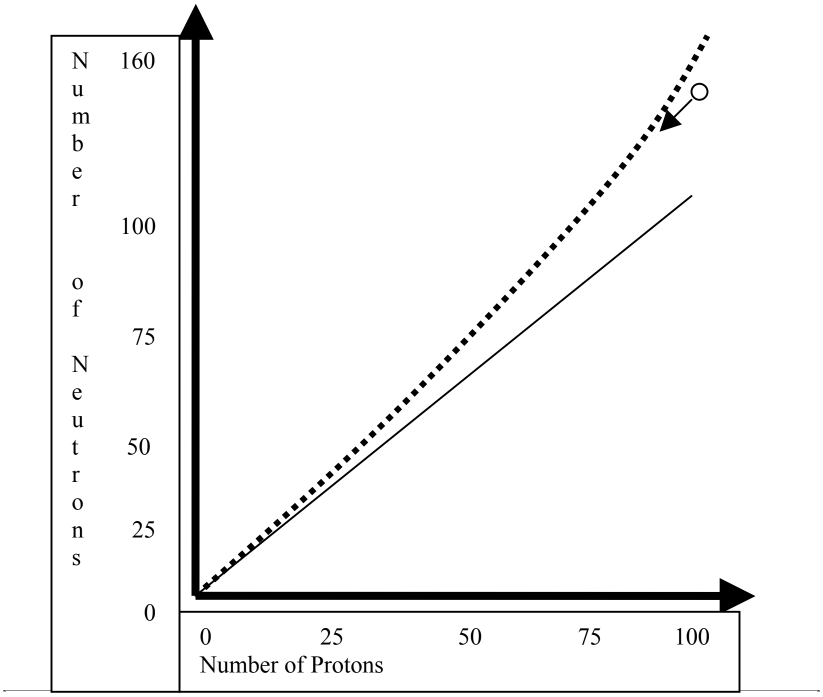


Table 3: An isotope with too few neutrons is always drawn below the dashed line of stability. The release of an alpha particle, however, makes the isotope more stable because it moves the position of the isotope down (two fewer neutrons), and to the left (two fewer protons), closer to the line of stability.

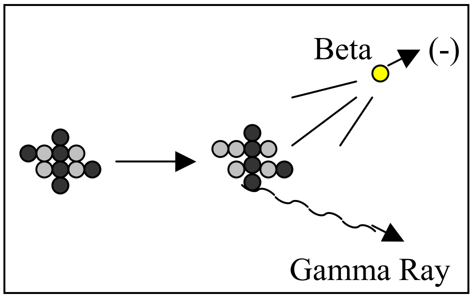
Since the loss of 2 protons changes the identity of the atom (the atomic number has decreased by 2), the nucleus that remains after an alpha particle is emitted is the nucleus of a different atom. Also, the loss of four nucleons (2 protons and 2 neutrons) means that the mass number of the new isotope is less than the mass number of the original isotope, by four.

Finally, the **gamma ray** is pure energy released by the nucleus as the nucleus tries to shed excess energy. The gamma ray usually accompanies the emission of an alpha particle or a beta particle. Releasing a gamma ray does not change the identity of the atom nor does it change the mass number of the atom since no mass is loss in this process. Gamma rays are released at the speed of light. Indeed, a gamma ray is a light ray in all ways, it is simply not visible to the human eye because it is outside of the range of frequencies that the eye can pick up. As a matter of fact, because of its very high frequency (and consequent high energy), a gamma ray passes right through the eye without interacting with the eye in any appreciable way.

The following illustration tries to summarize the processes discussed above. On the left, a beta particle is being emitted from the nucleus of beryllium-10, changing this isotope into boron-10. On the right, an alpha particle is being emitted from the nucleus of beryllium-8, changing this isotope into Helium-4. To simplify the pictures, the electron shells are not shown.

Beta Particle Emission
(Too many neutrons)

Beryllium-10 → Boron-10

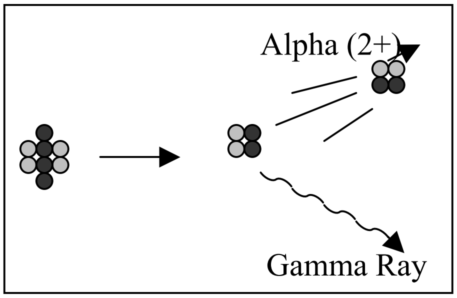


(4 p, 6 n) → (5 p, 5 n)

When a beta particle is created the nucleus changes a neutron into a proton and a beta particle. As a result, the nucleus loses one neutron and gains one proton. That means the atomic number increases by one and the mass number remains the same.

Alpha Particle Emission
(Too few neutrons)

Beryllium-8 → Helium-4



(4 p, 4 n) → (2 p, 2 n)

When an alpha particle is created the nucleus loses 2 protons and two neutrons. As a result, the atomic number decreases by two and the mass number decreases by 4.

So, there are three types of ionizing radiation: alpha particles, beta particles and gamma rays. Alpha particles are released from any isotope that has too few neutrons to hold it together. As a result, the atomic number of the isotope decreases by 2 and the atomic mass of the isotope decreases by 4. Beta particles are released from any isotope that has too many neutrons. As a result, the atomic number of the isotope increases by one and the atomic mass stays the same.

The Uranium-238 Decay Series

The radon story starts with a long-lived isotope (4.5 billion year half-life) of uranium, uranium-238. This isotope of uranium has 92 protons (as do all isotopes of uranium) and

146 neutrons. The mass number is therefore 92 + 146, or 238. Uranium is present in most soils and rocks to around one part per million (or, measured in terms of concentration, about 1 picocurie per gram). Even with all of these neutrons, however, uranium does not have sufficient numbers of neutrons to remain stable. It can be found on a neutron/proton chart below the line of stability. Therefore, it ultimately releases an alpha particle in an attempt to become more stable. The new isotope created as a result of the alpha particle release is thorium-234, with 90 protons and 144 neutrons. Thorium-234, however, is a beta emitter (too many neutrons) and changes into protactinium-234. It is easier to follow this decay series from a table, so let's start again with uranium-238, and put the whole decay series in table form. Read this table (table 4) from top to bottom. Each row gives the specific details of each isotope, including the half-life and the type of radiation (alpha or beta). When there is also a gamma ray emitted that has significant energy, or is useful to measure in the radon industry, an asterisk is used. These gammas will be discussed in more detail in the hands-on part of this presentation (5).

Isotope	**Atomic Number**	**Half-Life**	**Type of Radiation Emitted**
Uranium-238	92	4.5×10^9 y	alpha (4.2 MeV)
Thorium-234	90	24.1 d	beta (.01 MeV)
Protactinium-234*	91	1.17 m	beta (2.3 MeV)
Uranium-234	92	2.5×10^5 y	alpha (4.7 MeV)
Thorium-230	90	8.0×10^4 y	alpha (4.7 MeV)
Radium-226	88	1,620 y	alpha (4.8 MeV)
Radon-222*	86	3.82 d	alpha (5.48 MeV)
Polonium-218	84	3.05 m	alpha (6.00 MeV)
Lead-214*	82	26.8 m	beta (.65 MeV)
Bismuth-214*	83	19.7 m	beta (1.5 MeV)
Polonium-214	84	1.6×10^{-4} s	alpha (7.7 MeV)
Lead-210	82	19.4 y	beta (.017 MeV)
Bismuth-210	83	5.0 d	beta (1.16 MeV)
Polonium-210*	84	138 d	alpha (5.3 MeV)
Lead-206	82	stable	none

Table 4: The uranium-238 decay series. The energy of the alpha or beta particle is shown in parenthesis to the right of the particle. The units of energy are millions of electron-volts (MeV). Isotopes that have a significant gamma ray emitted are shown with an asterisk in the left-hand column.

There are a lot of fun things we can deduce from this chart. In fact, this chart will become a very important guide to us in the hands-on part of the presentation. Until then, however, here are a few things that the chart readily tells us: (1) A general rule (although not always correct) is that all of these isotopes are in secular equilibrium with each other as long as no chemical processes (natural or artificial) have been employed to chemically

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(5) Tables like this can be found in most books on radiation. This one was taken from (with some simplifications) Nuclear Radiation Physics-Third Edition, Lapp and Andrews, Prentice-Hall, 1968, page 73.

separate them from each other. What this means is that the radioactivity (counts per minute) is the same for uranium-238 as it is for thorium-234 as it is for protactinium-234 and so on, down the line. Therefore, where you find uranium-234, you will normally find radon-222. And, where you have radon-222, you will also have the short-lived radon decay products (polonium-218, lead-214, bismuth-214 and polonium-214). Hence, one can (theoretically, at least) use a Geiger counter to look for uranium-238 (using the alphas, betas and gammas from the first 6 members of the decay series down to radium-226) and, if uranium-238 is found, predict the presence of radon-222. Of course, since radon-222 is a gas and can leave the ground (leaving the uranium source behind), such a measure would not tell you how much radon is in the house, only that there is a strong possibility that radon-222 is being created and may be entering the house.

(2) From the chart, we see that radon-222 and two of its short-lived decay products, polonium-218 and polonium-214, have incredibly powerful alpha particles. The energetic alpha particles easily damage lung cells if they are released within the lungs. In fact, it is those alpha particles from polonium-218 and polonium-214, in particular, which cause the cell damage that leads to lung cancer.

(3) Notice, from the chart, that two of the radon decay products (lead-214 and bismuth-214) are significant gamma ray producers. Water filtration systems that can capture radon-222 and hold it (for example, charcoal filters) can eventually become dangerous gamma ray sources in themselves as these two radon-decay products come into secular equilibrium with the radon-222 captured within the charcoal. These gamma rays can be picked up with a Geiger counter.

These, and other aspects of the uranium-238 decay series, will be examined in more detail in the hands-on portion of this presentation. Next, let’s learn a little bit more about a Geiger counter.

How Does a Geiger Counter Work?

The heart of any Geiger counter is the Geiger-Muller tube. The tube is normally a sealed cylinder filled with argon gas at a low pressure (approximately 100 mm Hg, or about 1/8 atmospheric pressure). The tubes come in all sizes but are usually two to four inches long and about an inch in diameter. There are two electrical connections to the tube. The outside of the tube, which is usually made of metal or glass (painted with conductive carbon-black), is kept electrically negative, or grounded. A wire which goes down the center of the tube is kept electrically positive. The positive voltage can be anywhere from a few hundred volts to well over a thousand volts, depending upon the manufacture specifications of the tube. The voltage of a Geiger tube is regulated so that when the external radiation strikes the tube or penetrates the tube, the electrons which are knocked off of the gas atoms will pick up speed as they are drawn toward the center positive wire. These electrons, in turn, will cause additional ionization (secondary ionization) leading to a very large signal (voltage) from just one initial radiation pulse. This voltage range is called the Geiger region and makes the Geiger-counter a relatively sensitive instrument.

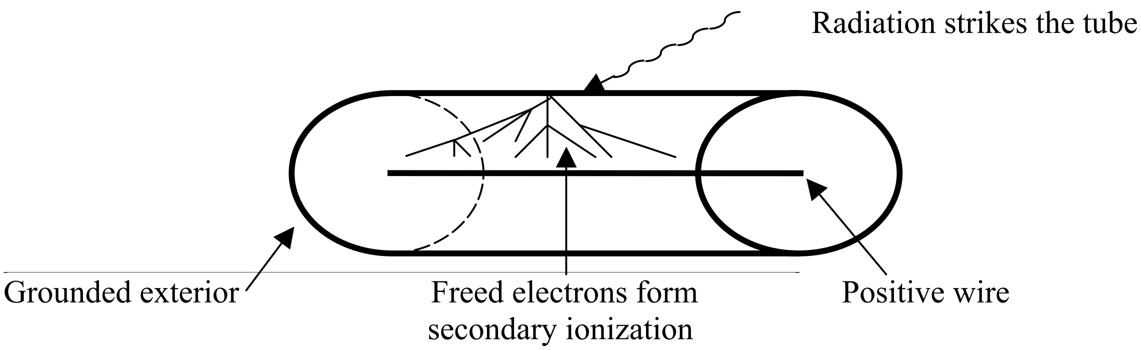

Figure 5: External radiation strikes the tube, causing ionization of the gas within the tube. The freed electrons, in turn, cause more ionization of the gas as they travel quickly to the positively charged wire.

Radiation that strikes the tube or enters the tube causes ionization of the argon gas within the tube. Because there is a strong positive voltage(6) on the wire, these free electrons drift toward the wire, picking up speed as they do so (about 10^6 cm/sec) (7). These electrons (and associated photons which are created in the process) then continue to ionize more gas atoms, called secondary ionization, building up into an "avalanche" of electrons striking the positive wire. This electron current can be measured by placing a one to ten-megohm resistor in series with the tube and the resultant voltage drop across that resistor can be anywhere from a fraction of a volt to 5 volts. Such a large voltage drop can easily be heard by connecting a typical 600-ohm headphone in parallel across the tube. (See figure 6).

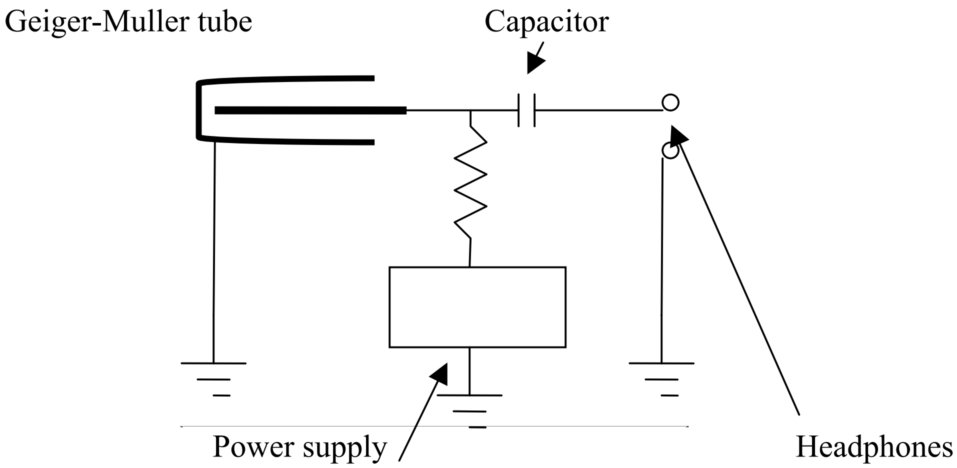

Figure 6: A simple schematic of a Geiger counter. The positive side of the power supply is connected to the anode (inside wire). Typical vales are 1 MΩ for the resistor and 10.0 pf (1000 volts) for the capacitor.

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(6) An ionization chamber which was run at a voltage less than the Geiger range would be more properly called a proportionality counter as it would produce a voltage pulse which would be proportional to the energy of the incoming radiation but would not create an avalanche of electrons as the Geiger tube would.

(7) Nuclear Physics: An Introduction, Burcham, W.E., McGraw-Hill, 1963, page 218.

There needs to be some method of stopping the electron current so that the Geiger tube can be "reset" to be ready to register the next pulse of radiation. There are three methods of stopping the current, or quenching.

(1) The one to 10-megohm resistor in the circuit drops voltage only when there is current (electrons flowing) in the Geiger tube. So, as the electron avalanche proceeds, the electron current flows across the series resistor, dropping voltage across the resistor and leaving less voltage to be applied to the Geiger tube. The Geiger tube then no longer has sufficient voltage to maintain the avalanche and the pulse is quenched. Because such a large resistor is required to get the necessary voltage drop, the recovery time, or time constant, of this circuit is very long. This makes this Geiger counter useless for very high radiation rates (large number of counts per minute).

(2) Instead of a large resistor, a smaller resistor can be used in series with another electronic gate, say a vacuum tube or a transistor, that allows current flow for a fraction of a second and then turns off, allowing the original voltage back onto the Geiger tube. Such "quenching circuits" allow counts as high as 10^4 counts per second to be picked up.

(3)Because "quenching circuits" require an extra electronic component, another, cheaper, way has been invented to reset the Geiger counter. In this method, a gas is introduced into the Geiger tube and this gas becomes the quencher. Alcohol (an organic material), with a ratio of about 10 %, has been used as the gas. How the alcohol works to bring about the quenching is rather ingenious.

So far, we have paid attention to the electrons flowing inside the Geiger tube. However, in order to understand quenching with an organic material, we have to look at the positive ions that are being created at the same time from the argon gas and the alcohol gas. These positive ions, which are being created from the same ionization that is stripping the electrons off of the otherwise neutral argon and alcohol atoms, are streaming toward the negative charge of the outer shell of the tube. As they move together, many of the argon ions and alcohol ions will collide. The argon atoms, having a larger affinity to electrons than the alcohol ions, will strip an additional electron off of the alcohol ion, which gives up this extra electron relatively easily (8). As a result of these collisions, and "stealing" of electrons, the argon ions are electrically neutralized and are no longer attracted to the negative charge. The alcohol ions, still heading toward the negative charge, pick up electrons off of the negative terminal. However, alcohol, unlike most gases, does not give off this additional energy by emitting photons (ultra-violet light) but, instead, dissociates (breaks into simpler molecules of hydrogen and carbon) So, without additional electrons being released from the photoelectric effect (from the usual ultra-violet light which would have been given off by argon ions attracting electrons from the negative terminal), the avalanche is no longer supported and the pulse ends(9).

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(8) The argon atom has an ionization potential of 15.7 electron volts while the alcohol ion can only hang on to its "extra" electron with an energy of 11.3 electron volts. Thus, argon ions can "steal" an electron from the alcohol ion with energy to spare. The extra energy, 4.4 electron volts, is used to dissociate the alcohol molecule. Eventually, all of the alcohol is dissociated and the quenching no longer works.

(9) Chlorine and bromine (halogens) are used as the quenching gas in neon or neon-argon tubes. The theory is much the same as the alcohol-quenched tubes, although the halogen-quenched tubes have an unlimited life.

Demonstrations Using a Geiger Counter

1. How to read the meter on a Geiger Counter

Almost all Geiger counters use the units of ionization (exposure) per time period, usually roentgens (R), or fractions thereof, per time period. Since one R indicates the presence of a lot of ionization, the scales are usually calibrated to read in thousandths of a roentgen, or milliroentgen per hour, abbreviated mR/hr. There is usually a switch on the face of the Geiger counter that allows one to chose a multiplying factor, so that if the switch is turned to “X1”, for example, it means to take the mR/hr reading and multiply it by one. One can usually find multiplication factors from 0.1 all the way up to 100. So, if you were to turn the multiplication factor to “X100” and the meter read 0.3 mR/hr, the correct exposure would be 0.3 X 100, or 30 mR/h.

Since the use of a capitol “R” to represent roentgen was only standardized in the 1956, by the Eighth International Congress of Radiology, some older Geiger counters will use a lower case “r” instead of the “R”. The lower case “r”, introduced in 1928 by the Second International Congress of Radiology, is still read as roentgens and mr/hr would be read as milliroentgens per hour.

Also, most meters convert the reading to counts per minute, abbreviated cpm or c/m. Usually both scales, mR/hr and cpm are found on the meter. The multiplication factor works exactly the same way for cpm as it does for mR/hr.

As explained on page 4, above, Geiger counters are designed to measure radiation exposure, or, how much radiation is in the immediate vicinity. They then convert this reading to exposure rate, or mR/hr.(10)

Health standards, however, have to take into account how the radiation reacts with (and damages) a person. Thus, it is helpful to be able to mentally convert from the exposure rate seen on the Geiger counter to the dose rate, also called the absorbed dose rate and finally, to the dose equivalent rate, which tells one how the different kinds of radiation affect the human body. Quite simply, and without any appreciable error, the exposure (in roentgens) is equal to the absorbed dose in tissue (in rad) is equal to the dose equivalent in man (in rem) for beta and gamma.(11)

(10) Some textbooks call exposure “exposure dose”. The units of “exposure dose” are nonetheless still roentgens and, of course, the units of “exposure dose rate” would still be mR/hr. Personally, I find the use of the word “dose” when talking about “exposure” to be very confusing.

(11) Exposure, absorbed dose and dose equivalent are equal numerically because one roentgen releases about 84 ergs in a gram of air and about 93 ergs in a gram of tissue (where an erg is a unit of energy in the metric system). Since one rad is defined as the amount of x-ray radiation absorbed dosage that releases 100 ergs of energy in a gram of tissue, saying that an absorbed dose of one rad comes from an exposure of 1 roentgen is 93/100 % correct as long as you are talking about x-rays and gamma rays. Finally, to take into account other types of radiation (beta, alpha, etc.), the unit of dose equivalent was introduced (rem). You can convert from absorbed dose to dose equivalent by multiplying by a quality factor. The quality factor for gamma and beta is 1 and for alpha is around 20. So, if one is only talking about beta and gamma, an absorbed dose of one rad delivers the same energy to tissue as the dose equivalent of one rem. Thus, in this sense, one roentgen equals one rad equals one rem.

Demonstration #1: **Measure the background radiation**. Move all radiation sources away from the Geiger counter. Open the cylindrical slide on the V-700 probe, exposing the small window. This window allows the Geiger counter to be sensitive to both gamma and beta radiation. It is called the beta window. Record the background radiation you are now reading. Background radiation (beta and gamma) is ____________________mR/hr.

Picture 1: A V-700 Geiger counter measuring about .05 mR/hr background. Notice that the so-called beta window is open.

We are now going to calculate your annual radiation dose equivalent based on the background reading you just measured. (Of course, this background reading is only appropriate for the particular location you are in at this time. You might want to repeat this background measurement and the annual radiation dose equivalent when you get home. Redo the background measurement where you live or where you spend most of your time.)

There are 8,760 hours in one year so, if you multiply the background measurement you just made by 8,760 you will be able to find the radiation you are exposed to in one year. Take the background measurement you found above and write it here: _________mR/hr. Multiply that by 8760 and write that here:________mR/yr. Example, if the background were .05 mR/hr, the annual exposure rate would be .05 X 8760, or 438 mR/year. Then, taking advantage of footnote 11, we can mentally convert to dose equivalent for beta and gamma (which is what you are measuring with this Geiger counter) and we find that the dose equivalent is 438 mrem/year, or 0.438 rem/year.

You might be interested in how this number, 0.438 rem/year, compares to occupational and residential standards in place nationally and in most states. Occupational (workplace) dose equivalent maximums are 5 rem/year for adults, 0.5 rem/year for minors and 0.5 rem/year for fetuses (pregnant women). General public (residential) dose equivalent maximum is 0.1 rem/year (100 mrem/year) and 2mrem/hr. You can see that our example (taken in the author’s home) exceeds the general public recommended maximum but is well below the occupational maximum (for non-pregnant adults).

Demonstration # 2: **Measuring the background radiation while eliminating alpha particles and beta particles.** Close the cylindrical slide on the V-700 probe, closing off the small beta window. The Geiger counter can now only read gamma rays. Record the background radiation you are now reading. Background radiation (gamma) is now ___________mR/hr.

Demonstration # 3: **Measure the background with a Geiger counter that is sensitive to alpha, beta and gamma radiation**. A V-700 Geiger counter will not work for this experiment. Such a Geiger counter will need to have a probe that has a mica window in it so that the alpha radiation can penetrate the window and be picked up by the Geiger tube. Background radiation (alpha, beta and gamma) is now ___________mR/hr.

Comparing the three numbers you measured for background radiation, which one, if any, is the largest? _______________ Does this make sense to you? __________________

2. Penetrating power of the three types of ionizing radiation.

The stopping power of any material to radiation depends upon four things: (1) The type of radiation (alpha, beta or gamma) (2) the energy of the radiation (3) the density of the material and (4) the thickness of the material. In this demonstration, we want to roughly determine the stopping power of common materials to the three types of radiation.

Imagine an alpha particle the size of a baseball. This baseball is thrown against a wall. You expect that the baseball would be stopped by any normal wall. However, on the atomic scale, the “baseball” alpha particle actually penetrates into the wall a distance depending upon how hard the “baseball” was thrown and the material the wall is made of. In fact, some alpha particles will be able to penetrate all the way through a wall if it is thin enough. For any given energy and type of radiation, including alpha particles, the percentage of particles that penetrate to any depth of a material is given by an exponential curve, shown below in figure (7) with no special units so that the graph can be used for the most general case. See Appendix One for a technical description of this curve.

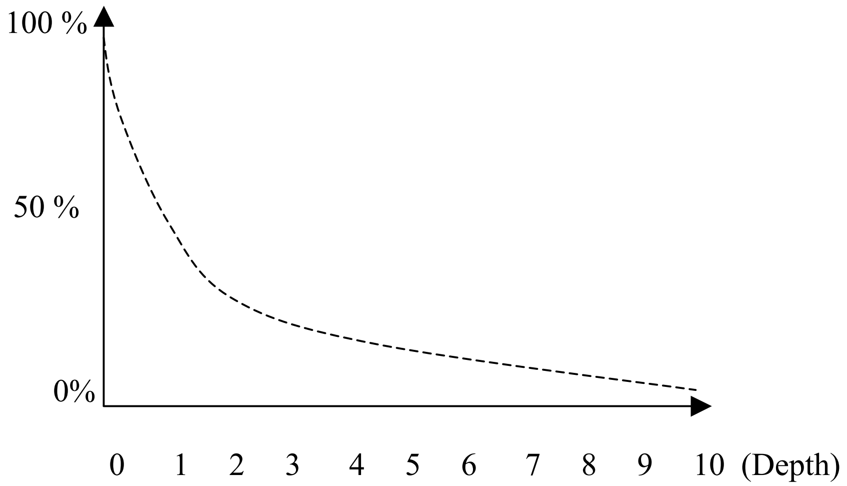


Figure 7: The percentage of radiation (vertical axis) that penetrates to various depths in some material. The horizontal axis has no units on purpose.

Demonstration 4: Measuring the penetrating power of alpha particles.

Because of their rather large size on the atomic scale, and their strong positive 2 charge, an alpha particle easily interacts with air (ionizing 30,000 air atoms pre cm) or any other material through which it is traveling.

For this experiment, you will need to use a Geiger counter other than the V-700; one that is sensitive to alpha particles.

Use the radiation source provided. Cover the source with a packet of about 20 sheets of paper. Move the Geiger probe to within an inch of the source (covered with the paper) and read the meter. Record the reading here: __________________.This source is primarily an alpha source (radium-226). However, other radiation can be emitted, too. So, the purpose of the first measurement, just finished, is to establish a background number with all of the alpha particles stopped but all other radiation allowed through the paper. This will be our reference number. It will be our “zero” alpha particle radiation. Whenever the Geiger counter reads this radiation again, in this experiment, we will know that all of the alpha particles have been stopped. **We will subtract this reference number from each reading in order to get the net radiation of the alpha particles penetrating the paper sheets.**

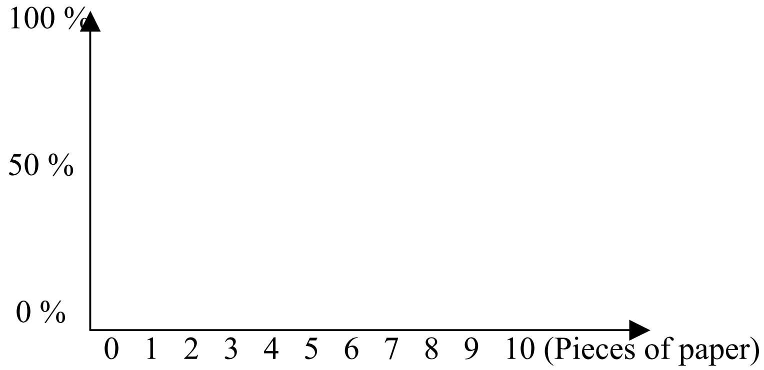
To measure the stopping power of paper to alpha particles from radium-226, remove the packet of paper from the source and place the Geiger tube one inch from the source. Record this reading under “Gross mR/hr” in the second column of row 1, below. Repeat this experiment, adding additional pieces of paper but keeping the distance between the source and the probe constant. Record those readings below in the second column. Subtract the reference number from each of the 10 readings in order to get the net counts of alpha particles. Record this number in the third column. Finally, divide each number in the third column by the net mR/hr in the first row (the number marked with the asterisk).

Multiplying by 100 will give the percentage of alphas penetrating to each sheet of paper.

Pieces of paper	Gross mR/hr	Net mR/hr	% of net alpha
0	____________	____________*	__100 %_
1	____________	____________	__________
2	____________	____________	__________
3	____________	____________	__________
4	____________	____________	__________
5	____________	____________	__________
6	____________	____________	__________
7	____________	____________	__________
8	____________	____________	__________
9	____________	____________	__________
10	____________	____________	__________

*divide this number into all of the Net mR/hr in column 2 (and then multiply by 100) to get the percentage of net alphas in column 4.

Try making a graph of your results below.



Does your graph have an exponential shape? ____________ (yes/no)

How many sheets of paper are required in order to drop the measured radiation to background (reference number) levels? ______________________________

Demonstration 5: Measuring the penetrating power of beta particles.

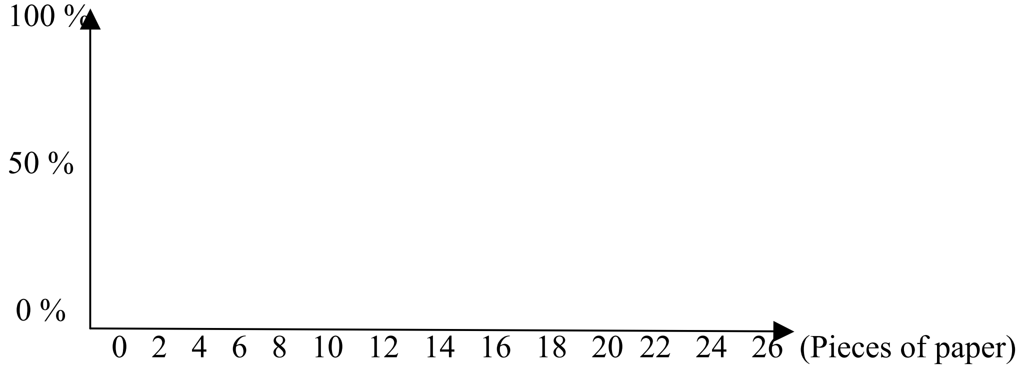
Because of their rather small size and their single negative charge, beta particles are more penetrating than alpha particles. Use the radiation source provided on the side of the V-700 Geiger counter. Rotate the cylindrical window on the tube, covering the beta window, preventing the Geiger counter from reading alphas and betas. Move the Geiger probe to within an inch of the source (covered with the paper) and read the meter. Record the reading here.__________________. This source is primarily a beta source (lead-210 and bismuith-210). However, other radiation can be emitted, too. So, the purpose of the first measurement, just finished, is to establish a background number with all of the beta particles stopped but all other background radiation allowed through the paper. This will be our reference number. It will be our "zero" beta particle radiation. Whenever the Geiger counter reads this radiation again, in this experiment, we will know that all of the beta particles have been stopped. **We will subtract this reference number from each reading in order to get the net radiation of the alpha particles penetrating the paper sheets.**

To measure the stopping power of paper to beta particles from lead-210/bismuth-210, open the beta window and place the Geiger tube one inch from the source. Record this reading under "Gross mR/hr" in the second column of row 1, below.

Repeat this experiment, adding additional pieces of paper but keeping the distance between the source and the probe constant. Record those readings below in the second column. Subtract the reference number from each of the 10 readings in order to get the net counts of beta particles. Record this number in the third column. Finally, divide each number in the third column by the Net mR/hr in the first row (the number marked with the asterisk) and multiply by 100. This will give the percentage of betas penetrating to each sheet of paper.

Pieces of paper	Gross mR/hr	Net mR/hr	% of net beta
0	______________	______________*	__100 %_
2	______________	______________	_________
4	______________	______________	_________
6	______________	______________	_________
8	______________	______________	_________
10	______________	______________	_________
12	______________	______________	_________
14	______________	______________	_________
16	______________	______________	_________
18	______________	______________	_________
20	______________	______________	_________
22	______________	______________	_________
24	______________	______________	_________
26	______________	______________	_________

Try making a graph of your results below.



Does your graph have an exponential shape? _______________(yes/no)

How many sheets of paper are required to drop the measured radiation to background (reference number) levels? ___________________________________

Demonstration 6: Measuring the penetrating power of gamma radiation.

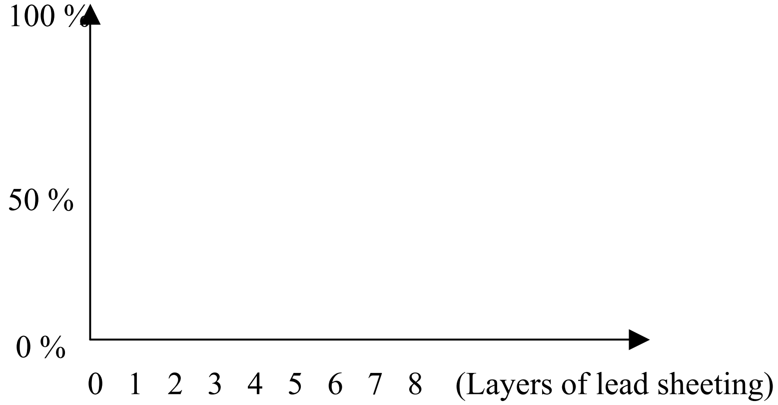
Gamma radiation is the most difficult radiation to stop because it has no charge and no mass. Put on a pair of plastic gloves so that you can handle the thin lead sheeting. Rotate the metal shell on the Geiger tube so that it closes the "beta window" making the Geiger probe sensitive to gamma radiation only. To find a reference level this time, the best we can do is measure the background radiation with the source far away. So, remove any radiation source from the vicinity and record the background radiation (with the beta window closed). Record the reference number here:__________________.

This source is a mostly gamma source (cobalt-60). To measure the stopping power of lead sheets (each with a thickness of .032 inches) to gamma radiation (cobalt-60), move the Geiger probe to within one inch of the source with no lead sheets in place. Record the reading here in the first row, column two, under "Gross mR/hr".

Repeat this experiment, adding additional pieces of lead sheets but keeping the distance between the source and the probe constant. Record those readings below. Now, subtract the reference number from the Gross counts to get the Net counts and divide the net counts by the Net mR/hr (the number with the asterisk) and divide by 100 to get the percentage of net gamma.

Number of lead sheets	Gross mR/hr	Net mR/hr	% of net gamma
0	______________	______________*	__100 %_
1	______________	______________	__________
2	______________	______________	__________
3	______________	______________	__________
4	______________	______________	__________
5	______________	______________	__________
6	______________	______________	__________
7	______________	______________	__________
8	______________	______________	__________

Try making a graph of your results below.



Does your graph have an exponential shape? ______________(yes/no)

How many sheets of lead are required to drop the measured radiation to background levels? _____________________________

3. Identifying radiation

Demonstration 7: **Using the source provided (a mantle), try to identify the type(s) of radiation given off of the mantle.** Put the source about one inch away from the probe. Have the beta window closed on the V-700 probe so that the probe is only sensitive to gamma radiation. Is your Geiger counter picking up any counts? _________(yes/no). Record the gamma radiation, if any, here ______________________mR/hr. Now, open the beta window, allowing your Geiger probe to be sensitive to beta particles. Cover the source with enough sheets of paper to stop any potential alpha particles coming from the source. Refer to your answer above where you determined the number of pieces of paper that essentially stopped all of the alpha particles. Use that same number of sheets of paper to cover the source. Are you picking up any radiation now? _______ (yes/no). Record the radiation here: _________mR/hr. Since you may be picking up some gamma radiation along with the beta radiation, if you really want to know how much of the radiation you are now reading is beta, you would have to subtract off the gamma radiation (if any) from your present reading. We will not do that.

Finally, using a Geiger counter sensitive to alpha particles, remove the paper shielding the mantle. Did the number of counts increase? ___________ (yes/no). What is the radiation reading now? ______________mR/hr. The increase, if any, had to be due to the addition of some alpha particles to the radiation stream. In this way, you can identify the makeup of any unknown radiation source.

Demonstration 8: Where is that radon coming from? Most likely, the radon is being created in the soil and/or rock right under the house. Sometimes, there is so much uranium-238 and/or radium-226 that they can be measured above background radiation. Using the source provided, some rocks (mostly Pikes Peak granite) from a building site in Colorado Springs, CO, place the Geiger probe on top of one of the rocks. Can you measure any radiation above background?_________________ (yes/no). If so, what is the reading?______________?
Determine if the radiation is beta or gamma, or a combination of these two by closing the beta window and seeing if you still have the same amount of radiation, or less. Conclusion; the gravel is emitting mostly _____________________ radiation.

Demonstration 9: Did you know that TV sets make great radon decay product (RDP) collectors. In fact, running TV sets in a house while making a RDP measurement probably skews the equilibrium ratio (ER) measurement artificially low. You have probably noticed that the face of a TV screen contains a very high static voltage while the set is on. The screen, because of this large voltage, attracts dust particles to it. These dust particles already have RDP's attached to them. So, the front face of a TV set (not an LCD or plasma screen) soon gets covered with RDP's, especially the short-lived lead-214, bismuth-214 and, eventually, the long-lived lead-210. You can measure this radiation directly by placing the probe right up to the face of the TV set and you will notice a fairly large increase above background radiation (two to four times above background even in a house with radon as low as 2 pCi/L). Or, you can wipe the face of the TV screen with a cotton smear and measure the radiation on the cloth with your Geiger counter.

Picture 2: A Geiger counter held up to a television screen picks up residual radiation from the radon decay products attracted to the screen. The dial is reading 0.1 mR/hr, about two times above background for this location.

Using the smear provided (12), wipe the face of a TV screen and measure the radiation coming off of the cloth. Record that reading here____________________mR/hr. Experiments conducted by the author shows that most of this radiation is beta radiation coming from the isotopes listed above. Because of the half-life of lead-214 and bismuth-214, you must measure the swipe fairly quickly after taking it or you will only measure the long-lived lead-210/bismuth-210 (13).

Demonstration 10: **Measuring the radiation from water filtration units.** Many of you work in states that have a lot of radon in the water. Often, your clients will use charcoal filtration (granulated activated charcoal, or, GAC) units in order to filter out the radon. The units collect the radon which soon is in secular equilibrium with the decay products of lead-214 and bismuth-214. It is possible for the gamma radiation coming off of these two isotopes to penetrate the metal or fiberglass container holding the charcoal. Sometimes, this gamma radiation can reach unacceptable levels. A Geiger counter is a very useful tool to have in order to check the radiation levels outside of the container.

Close the beta window on the Geiger counter and place the probe close to the sample of activated charcoal or GAC unit that has been provided. Do you measure any radiation? __________ (yes/no). Close the beta window on the Geiger tube. Does the radiation decrease significantly? GAC units must, therefore, be _______________ sources.

You should refer to your state guidelines for acceptable levels of gamma radiation from GAC units. Carry your Geiger counter with you on all jobs so that it is available should you run across a GAC unit. Here are some general guidelines developed by various agencies over the years, but, always check with your state radon contact person or the state health department for exposure regulations in your area. They always take precedence over general guidelines.

General Exposure Guidelines:

When measuring a suspected radiation source, stand approximately one meter (3 feet) from the source or the surface through which the radiation is emanating. A reading of 10 mrem/hr (0.1 mSv/hr) indicates an area that is not safe to stay in and a reading of 10 rem/hr (0.1 Sv/hr) or higher indicates an area that should not be entered unless the person is willing to accept permanent radiation damage, including later stochastic illnesses (like cancer) or death (14). (A GAC unit will produce 1 mrem/hr for each 10,000 pCi/L of radon in the water at the tank surface.)

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(12) Smears are 1 ¾"diameter cotton from D.A. Services at http://www.daway.com.

(13) Thanks to Mr. George Dowell, GEOelectronics, 56791 Rivere Au Sel Estates Place, POB 461, New London, MO 63459, GEOelectronics@netscape.com, for alerting me to the build up of RDP's on a TV screen and the fact that the screen is positively charged with respect to ground. He is also the individual who provided me with the Fiesta Ware and the saucer used later in demonstration

(14) Radiation Control, 6CCR 1007-1-Part 4, Department of Public Health and Environment, Hazardous Materials and Waste Management Division, State of Colorado, 2004.

Demonstration 9: Measuring the radiation off of potassium chloride.

Most soft water conditioners use regular salt, sodium chloride, to soften the water. However, people who are sensitive to salt prefer to use potassium chloride instead. The potassium, as found in these units, is made up of Potassium-40 (.01 %) and potassium-39 (93 %). Potassium-39 is stable and produces no radiation. Potassium-40, however, is quite radioactive with a 1.5 MeV gamma and 0.5 MeV beta. So, it is possible for a soft water conditioner to become a radiation source in a house. You, as a radon professional, can carry a Geiger counter with you to check this additional source of radiation. You will probably find, in real life, that the water inside the unit shields the home owner from the beta radiation but you may find examples where the gamma is measurable even outside of the unit. For this demonstration, a sample of potassium has been provided for you just as it comes from a water treatment company. Measure this sample and see if you can detect gamma rays above the background? Detect any?_________________________(yes/no)

Demonstration 10: Common household items may also be radiation sources.

In the author's home, for example, a quick survey showed two kinds of glassware which had radiation several times above background. In one case, the glass, called Fostoria, had no glaze on it, so it appears that the glass itself (probably the lead in the glass) is radioactive. In the other case, the cup was covered in a glaze and it appears that the glaze contains the radioactive material. For this demonstration, which is to be done after the completion of the course, you are to use a Geiger counter to survey the various items in your own home. You may want to start with the dishes, as the author did, but don't neglect other objects in the house (window glass, welding rods, smoke detectors, flower pots, etc.)

Picture 3: Fostoria glassware is approximately eight times above background.

Picture 4: Radiation six times above background found in this piece of China.

The instructor has provided two examples of dishware. The large orange plate was sold by Sears for years. It is called Fiesta Ware. Measure it at its surface with beta window open and closed. Write your results here: Reading with beta window open: __________mR/hr. Reading with beta window closed (only gamma): __________mR/hr.

Now measure the radiation coming off of the small saucer. The manufacturer of the saucer is not known. Reading with beta window open: _______________mR/hr. Reading with beta window closed: _________________ mR/hr.

4. Half-Life

We have saved the best demonstration for last. In this demonstration, we will generate a radioactive gas inside of a container and then we will measure the radiation inside the container for 3 minutes. We will see the radiation decrease over time and will be able to roughly find the half-life of this radioactive material. For this demonstration, a Geiger counter sensitive to alpha particles must be used.

Demonstration 11: Finding the half-life of thoron.

Thoron gas, also called radon-220, comes from the radioactive decay of thorium- 228. See table 5, below:

Isotope	**Atomic Number**	**Half-Life**	**Type of Radiation Emitted**
Uranium-236	92	$2.3 \text{ X } 10^{7}$ y	alpha
Thorium-232	90	$1.4 \text{ X } 10^{10}$ Y	alpha
Radium-228	88	5.75 y	beta
Actinium-228*	89	6.13 h	beta
Thorium-228	90	1.9 y	alpha
Radium-224	88	3.62 d	alpha
Radon-220	86	55 s	alpha
Polonium-216	84	0.146 s	alpha

Lead-212*	82	10.6 h	beta
Bismuth-212*	83	60.5 m	beta
Polonium-212	84	0.298 X 10^{-6} s	alpha
Lead-208	82	stable	

Table 5: The decay scheme for Uranium-236 which leads to thoron gas, radon-222 with a half-life of 55 seconds. Significant gamma emitters are shown with an asterisk

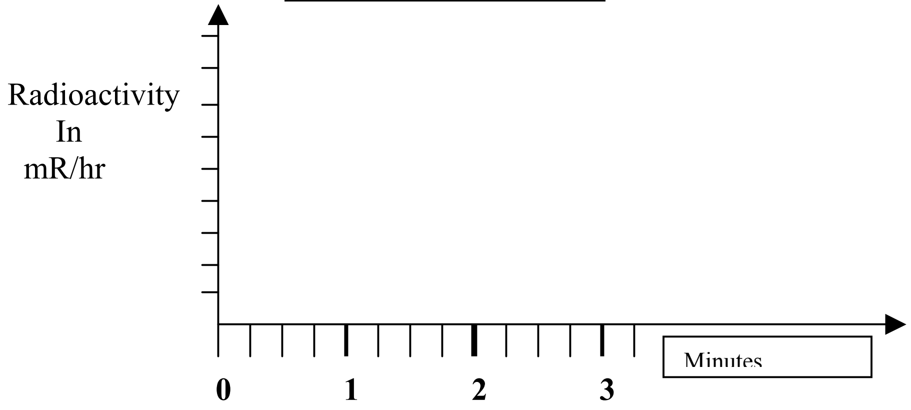
In order to measure the half-life of thoron, place the Geiger counter probe into a zip lock plastic bag, resealing the plastic bag as well as possible using the zip lock feature. A small hole has been cut out of one corner of this zip lock plastic bag for the later introduction of thoron gas.

Our thoron source will be the air/gas mixture which we will prepare inside of a second plastic bag. 10 mantles have been placed inside of a second plastic bag provided. This second bag has an inexpensive small valve system at one end.

Radon-220 will start building up in this container right away. The longer you leave the mantles inside of the container, the larger radiation signal you will get, but even 5 to 10 minutes is sufficient for this experiment. After 10 minutes, or so, allow the thoron gas to escape from the plastic bag through the small valve into the original plastic bag by inserting the nozzle on the valve of the second bag into the small hole in the corner of the zip lock bag, open the valve and press down on the second bag with the palm of your hand, expelling the thoron into the ziplock bag.

Immediately record the radiation as reported by the Geiger counter. Continue to do this every 15 seconds over about a 3 minute period. Make a graph of the results here. By examining the completed graph, you should be able to estimate the half-life of thoron. The accepted value is about one minute.

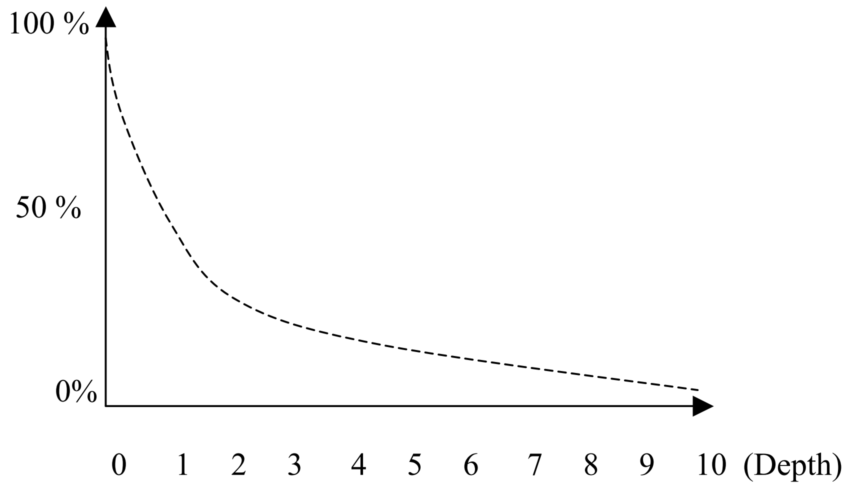
Your value of the half-life is ____________________ minutes.



Appendix One: The Exponential Absorption Curve

The following is fairly difficult and requires some mathematics. It is intended to be supplemental material, only, and is not an integral part of this presentation.

As discussed in Demonstration 2, radiation can penetrate material. However, the penetration depth is not a simple number, but an equation. Alpha particles, for example, are often characterized by saying that they can not go through a single sheet of paper. However, that is an over simplification. It is true that some alphas will be stopped by the sheet of paper, but others (even with the same energy) will penetrate the paper. If one was to chart the fraction, or percentage, of alpha particles that penetrated various depths of paper, one would get a curve that showed decreasing percentages of alpha particles for increasing thickness of the paper absorber, something like this:



Mathematically, this curve can be accurately described as an exponential curve. Specifically,

$$\text{Intensity at any depth} = (\text{Initial Intensity}) \cdot \exp(-\mu_l(\text{depth}))$$

Where Intensity is the energy of the radiation, **μ_l is the linear absorption coefficient** and depth is the thickness of the paper (or any absorber) at the point being looked at. The linear absorption coefficient depends upon the material and the energy of the incoming beam of radiation. **It also gives you the fraction of the incoming beam that is absorbed by the material per gram of material of unit thickness (usually one cm)**. For example, for the most prevalent gamma ray coming from the radon decay product lead-214, the linear absorption coefficient is 0.3/cm for aluminum and 1.0/cm for lead. This means that a beam of low energy gamma rays from lead-214 will be diminished by 30 % for every cm of aluminum and 100 % for every cm of lead. Another way of looking at it is that 5 cm of aluminum will diminish the radiation down to 0.3 X 0.3 X 0.3 X 0.3 X 0.3 = .00243, or 0.243 % of its original level. In other words, a small amount of gamma radiation will make its way through even 5 cm of aluminum. On the other hand, one cm of lead is sufficient to stop 100 % of these same gamma rays.

It can be shown with a little math that the linear absorption coefficient is equal to 0.693/HV where HV is the so-called half-length. In other words, HV is the thickness of the material that would remove half of the alpha particles out of the beam of radiation. Or,

$$\mu_l = 0.693/HV.$$

So, in your various demonstrations, you could determine visually the half-length by looking at the graphs you made, plug that number into the above equation and easily find the μ_l, the linear absorption coefficient for, say, paper.

Appendix Two: Derivation of the Working Level Unit

All of us have learned about the unit for measuring radon decay products, the working level, or WL. However, very few of us have seen the derivation. This derivation is fairly difficult and is included here as an extra and is not part of the presentation.

By definition, 1 WL is the total amount of alpha particle energy that would potentially be released by the short-lived radon decay products in secular equilibrium with 100 pCi/L of radon-222. We use this definition to calculate the alpha particle energy from each radon decay product and add up all the energies. That will be 1 WL.

To begin with, it is known that the activity of a radioactive isotope is proportional to the number of radioactive atoms (N) in the sample. That can be written as an equation,

$$dN/dt = - \lambda N, \qquad \text{Equation (1)}$$

where the left hand side, -dN/dt is the number of decays per second and λ is the proportionality constant. It can also be shown that λ is equal to $0.693/t_{1/2}$, where $t_{1/2}$ is the half-life. So, one can find the number of radioactive atoms of any isotope if you know the activity and the half-life. For example, if you have 100 pCi/L of radon, which has a half-life of 3.8 days (5501 minutes), the number of radon atoms within that liter is found by calculating λ,

$$\lambda = 0.693/t_{1/2} = 0.693/5501 \text{ m} = .0001259/\text{m}.$$

Then, changing pCi to decays per minute, -dN/dt = 100 pCi X 2.22/m/pCi = 222/m.

Then we can find N using equation (1). Solving equation (1) for N, gives us:

$$N = (-dN/dt)/\lambda$$

$$N = (222/m)/ (.0001259/m) = 1.76 \times 10^6 \text{ radon atoms.}$$

If we did our math right, that means that in every liter of air that contains 100 pCi of radon, there are over 1 million radon atoms within that liter, just waiting to have their turn at decaying.

How is this going to help us find out what one working level is? Well, we simply do the same thing for each of the radon decay products, assuming that each one, in turn, is in secular equilibrium with the radon in the room. That is, we assume that each of the radon decay products is at 100 pCi/L.

Then, we find out how many atoms , N, there are of each of the radon decay products and multiply that number by the energy of the alpha particle it will emit (or the alpha particle it will emit when that radon decay product eventually becomes an alpha emitter).

Let's start with the first radon decay product. From table 4, we see that it is polonium-218. It has a half-life of 3.05 minutes and it produces an alpha particle with an energy of 6.00 MeV. Since, by assumption, its activity is 100 pCi/L (it is in secular equilibrium with the radon), dN/dt must be 222/m again. Then we can find λ,

$$\lambda = 0.693/3.05 \text{ m} = .2272/\text{m}$$

and, from equation 1, we can find the number of polonium-218 atoms within this liter;

$$N = (222/m)/ (.2272/m) = 977 \text{ atoms.}$$

Each of one these atoms will release a 6.00 MeV alpha particle, giving a total energy of:

Energy (Po-218) = 977 alphas X 6.0 MeV/alpha = **5862 MeV**.

Before we leave polonium-218, let's remember, from the decay series, that every one of these 977 polonium-218 atoms will eventually become polonium-214, releasing 977 alphas with an energy of 7.7 MeV, each, for a total energy of:

Energy (Po-218 → Po-214) = 977 alphas X 7.7 MeV = **7523 MeV**.

We continue now with the next radon decay product, lead-214. Lead-214 is a beta emitter with a half-life of 26.8 minutes. How many lead-214 atoms will there be in a liter of air? Solving for λ, again, we find that it is:

$\lambda = 0.693/26.8 \text{ m} = .0259/\text{m}$, and using equation 1,

$$N = 222/m/(.0259/m) = 8585 \text{ atoms.}$$

Now, lead-214 does not make any alphas, but when lead-214 becomes Po-214, each one of those 8585 Po-214 atoms will make a 7.7 MeV alpha particle, for a total energy of:

Energy (Pb-214 → Po-214) = 8585 alphas X 7.7 MeV = **66,105 MeV**.

Bismuth-214 is next, with a half-life of 19.7 m, releasing a beta with energy of 1.5 MeV. Following the same prescription as before, we can find that there are 6310 atoms in the liter of air. When the Bi-214 becomes Po-214, all 6310 alphas will release 7.7 MeV each, for a total energy of:

Energy (Bi-214 → Po-214) = 6310 alphas X 7.7 MeV = **48,593 MeV**.

Finally, there is the polonium-214 atoms themselves. There are not very many of them in a liter of air that has 100 pCi of radon in it. Once again, finding λ:

λ = 0.693/(1.6 X 10-4 s X 1 m/60 s) = 25987/m

which means that there are only:

N = 222/m/(25987/m) = **0.008543 atoms** of Po-214 in the liter of gas, not counting the ones being made from the disintegration of the earlier radon decay products.

Multiplying .008543 alphas by 7.7 MeV, we see that the contribution of Po-214 to the total energy is a measly **0.0658 MeV.**

We now add up all of the alpha energy made from the radon decay products in equilibrium with 100 pCi of radon, in a liter of air, and find that the total energy is:

5862 MeV + 7523 MeV + 66105 MeV + 48593 MeV + .0658 MeV = **1.28 X 10^5 MeV.**

This is usually rounded of to 1.3 X 10^5 MeV. Therefore, 1 WL is defined as 1.3 X 10^5 MeV, and now you know why.