Radiation Dosage and Natural Radiation

We previously introduced concept of the activity of an isotope, which is a measure of the number of decays/second. The units of activity are 1 Curie = $3.7x10^{10}$ decays/sec. A more common unit used in our laboratory is a micro-curie, which is equal to $3.7x10^4$ = 37,000 decays/sec. Another unit that is used is the Bequerel, 1 Be = 1 decay/sec. Activity is a property of a radioactive isotope, and can be very precisely defined. However, in biology we are also interested in how much damage radiation does to living organisms. We refer to radiation damage as dosage. The more dosage one receives, the more the cells are damaged.

Quantifying dosage is not as straight forward as determining a value for the activity of an isotope. This is because different types of radiation cause damage in cells in different ways. It turns out that a fairly good measure of dosage is the amount of energy the radiation deposits per unit mass of the organism. The more radiation energy absorbed per mass, the more damage is done to the cells, and this is the accepted quantity that one associates with the dosage received. The units of energy absorbption are energy/(mass of tissue), and specifically the most common unit is the Rad:

$$1 \text{ rad} = (100 \text{ ergs of energy absorbed})/(\text{gram of tissue})$$

The rad is a well defined quantity. However, since different types of radiation causes different amounts of damage, the number of rad's do not give a complete picture of how much damage is done to the cells. For example, 1 rad of gamma radiation to an organism will cause less cell damage than 1 rad of alpha radiation. For a more precise description of dosage one multiplies the number of rad received by a factor called the RBE:

$$\text{REM} = (\text{rad})\ (\text{RBE})$$

The acronym REM stands for Roentgen-Equivalent-Man, and is approximately the energy absorbed in tissue equivalent to 1 Roentgen of X or gamma ray radiation. RBE stands for Relative Biological Effectiveness, and is an estimate of the relative damage done by different types of radiation compared to X-rays. We list below the RBE factor for some common types of radiation:

RBE	Type of Radiation
1	for X-rays, gamma, and beta radiation
10	for alpha radiation
3	for slow neutrons
10	for fast neutrons

From the RBE we see that 1 rad of alpha particles does 10 times as much cell damage (10 times the dosage) as 1 rad of gamma radiation. The values of the RBE are not precise well measured quantities. They are estimates, and as our knowledge about radiation damage improves, these numbers might change.

Dosage is a measure of the radiation damage done per gram. So one can talk about dosage received in a certain part of the body, or about whole body dosage. For alpha and beta radiation, which is absorbed near the skin, the dosage is usually localized to a small area near or on the skin. For gamma radiation, which penetrates through the body, one receives dosage throughout the entire body. For medical applications, one wants to deposit the energy of radiation in a very small volume around a cancerous region. For cancer therapy the dosage needs to be very high in a small volume, and zero elsewhere. If an organism absorbs radiation energy, it begins to repair itself. For low dosages, the healing process can be complete. However, if the dosage is too large, permanent damage and even death can occur. Below is a list of dosage levels for a single exposure to radiation in which the whole body absorbs the energy.

One time Whole Body Exposure to Radiation

Dosage	Effects
0 - 25 Rem	No obvious Injury. No detectable clinical effects Probably no delayed effects.
25 - 50 Rem	Possible blood changes, but no serious injury.
50 - 100 Rem	Blood-cell changes, some injury, no disability
100 - 200 Rem	Nausea and fatigue, Injury, possible disability, Shortening of life expectancy
200 - 400 Rem	Injury and disability certain, death possible
400 Rem	50 percent fatal
600 or more Rem	fatal

None of us will hopefully never receive 25 REM, but you might wonder how much radiation we receive in our daily activities. We receive radiation due to natural sources on the earth, cosmic rays, nuclear fallout, and during medical diagnosis (e.g. X-rays). The dosage will vary from place to place, but on the average is it around 360 mRem/year. One mRem = 1 milli-Rem = 0.001 Rem. Specifically, the average radiation does in the US from a recent source are listed below. Note that cosmic ray radiation varies a lot with elevation. At sea level we are exposed to around 30 mRem/year, and at 20,000 feet elevation, the dosage rate can be as high as 500 mRem/year.

Radiation Source	Average Annual Whole Body Dose (mRem/year)
Cosmic Rays	30
Terrestrial Sources	30
Radon	200
Internal (K40, C14)	40
Diagnostic X-Rays	40
Nuclear Medicine	15
Consumer Products	10
Fallout, Air Travel	2
Average Annual Total	360

Below is listed the average doses from some daily activities:

Activity	Dose (mRem/year)
Smoking	280
Dental X-ray	10 per X-ray
Chest X-ray	10 per X-ray
Drinking water	5
Plane Flight cross Country	2

For workers in nuclear power plants, nuclear submarines, and other occupations where exposure can be high, the dosage limit set by the U.S. government is 5 Rem/year. If one works 50 hours/week for 50 weeks/year, this dosage comes out to 2 mRem/hour. The 2 mRev/hour is the limit that we have in our laboratory. The radiation safety officer, has to be sure that the sources are properly shielded so that no one is exposed to more than 2 mRem/hour if they work 2500 hours/year or 5 REM/year. Hand held Geiger counters are often calibrated in units of mRem/hour, and can be used used to test work areas. The Geiger counter is, however, usually calibrated for gamma rays from Cs^{137}.

Whenever working with isotopes or nuclear radiation, one should always try to minimize the dosage to be as small as reasonably achievable. An acronym for this safety mentality is *ALARA*: As Low As Reasonably Achievable. The exposure that one receives can be reduced by using as *small of an activity* as possible, by *limiting the time* that one receives exposure, and by keeping yourself as *far away from the sources of radiation* as possible. By minimizing exposure time, maximizing the distance, and minimizing activity used, one can reduce the possibility of radiation damage, and in the laboratory it is important to keep these safety ideas in mind.

Basic Laboratory Safety Rules

1. Eating, drinking and smoking are prohibited in the laboratory.
2. Always wear a monitoring device (your film badge) when working in the lab.
3. Wash your hands immediately after leaving the laboratory. Actually, hands and clothing should be monitored when leaving the laboratory, but since we are using only sealed sources this is probably not necessary.
4. Use tongs or thumb forceps when handling radiosiotopes.
5. All accidents involving personal or work-area contamination are to be reported immediately to the instructor.

We finish this chapter with some calculations in which we estimate the dosage received. We start with the effect of distance from the source: the inverse square law.

Inverse Square Law:

If the source of radiation is a point source, then the intensity of the radiation decreases as the inverse square of the distance. This "inverse square law" decrease of intensity is a result of the fact that the radiation is emitted equally in three dimensions. Suppose we have a "point" (or small) source of radiation that emits G gamma's per second. Let's also assume that the gammas are emitted isotropically. By isotropically, we mean that the gamma particles are emitted ourward from the source with an equal chance to travel in any direction. Suppose that a surface of area A is located a distance r away from the source.

How many gamma's pass through the surface of area A per second? If we assume that the gammas are emitted away from the source isotropically, then they will be uniformly distributed on the surface area of a sphere of radius r. Since the area of the surface of a sphere is $4\pi r^2$, we have:

$$\gamma' s\ passing\ through\ area = G\frac{A}{4\pi r^2} \tag{1}$$

Since the intensity of the radiation is just the number of particles passing through the surface per second, the above equation states that the intensity decreases with the distance from the source as the inverse square of the distance. If one moves **twice as far away** from a radioactive point source, the intensity **decreases by a factor of** 4. If one moves **three times as far away**, the intensity **decreases by a factor of 9**. Moving 5 times as far away decreases the intensity by a factor of 25!, etc. **Distance is a very important factor in reducing ones exposure**!.

Consider the following example. Suppose we have a cube of water located a distance of 5 cm from a 1μCi source of Cs^{137}. Suppose that the cube has dimensions of 2 cm by 2 cm by 2 cm, and that the radiation passes through perpendicular to one side. Find the number of 662 gammas incident on the side of the cube per second. This can be done as follows:

A 1μCi source undergoes $37,000$ decays per second. The yield factor for the 662KeV gamma from Cs^{137} is 0.85 gamma's per decay. Thus, the source emits $37,000(0.85) = 31,450$ gamma's/sec. Since the radiation is emitted isotropically, the $31,450$ gammas are uniformly distributed over the surface of a sphere of radius 5 cm. The number that pass through the surface of the cube is:

$$\begin{aligned} \frac{Number\ of\ gammas\ through\ surface}{sec} &= 37,000(0.85)\frac{4cm^2}{4\pi 5^2 cm^2} \\ &= 400\frac{gammas}{sec} \end{aligned}$$

At 10 cm from the source, only 100 gamma/sec would pass through the surface, and at 20 cm only 25 gammas pass through the surface of the cube.

Geometry often plays an important role in the description of nature. The inverse square law is one such example, and shows up in many situations in physics. The intensity of light from a point source decreases as the inverse square of the distance from the source. Sound intensity, the strength of the gravitation field and the strength of the electrostatic field also decrease as the inverse square of the distance from a point source. What all these applications have in common is that the energy (or force) eminates from a point source. The inverse square factor comes from the surface area of a sphere, which equals $4\pi r^2$. If we lived in a 2 dimensional world, the intensity would decrease as $1/r$. If we lived in a world with 4 spacial dimensions, the intensity would decrease as $1/r^3$. When you verify the inverse square law in your laboratory experiment, you have just proven to yourself that you live in a world with 3 spacial dimensions.

Examples of Dosage Calculations

As an example, we will calculate the dosage that a person receives by standing 5 meters away from a one Curie source of 600 KeV gamma particles. Suppose the yield for the decay is 0.80 gamma's per decay. This is a very active source, one Curie equals 3.7×10^{10} decays per second. Lets take the dimensions of the person to be 2 m tall, 30 cm wide, and 20 cm deep, and let the radiation hit his front side.

1. Use the inverse square law to determine the number of particles hitting his front side per sec:

$$\begin{aligned} \gamma's/sec &= 3.7 \times 10^{10}(0.8)\frac{2(0.3)m^2}{4\pi 5^2 m^2} \\ &\approx 5.65 \times 10^7\ \gamma's/sec \end{aligned}$$

2. Determine the number of gamma's that pass through the person. To do this, we need to know the attenuation coefficient. For water, $\mu = 0.896$ cm^2/g for 600 KeV gammas. Since the density of water is $\rho = 1.0$ g/cm^3, the linear attenuation coefficient is $\alpha = \rho\mu = 0.0896$ cm^{-1}. Since the person is 20 cm thick, we have:

$$\begin{aligned} \gamma's/sec &= 5.65 \times 10^7 \times e^{-20(0.0896)} \\ &\approx 9.94 \times 10^6\ \gamma's/sec \end{aligned}$$

Thus the number of gamma's absorbed by the person per second is:

$$\gamma's\ absorbed/sec \approx (5.65 - 0.99) \times 10^7 = 4.66 \times 10^7 \gamma's/sec \tag{2}$$

3. The radiation energy absorbed by the person every second is just

$$\begin{aligned} Energy/sec &= (4.66 \times 10^7 \gamma/sec)(600000 eV/\gamma)(1.6 \times 10^{-12} ergs/eV) \\ &= 44.7\ ergs/sec \end{aligned}$$

4. The dosage is the energy absorbed per mass. The persons volume is (200 cm)(30 cm)(20 cm) = 120000 cm^3. The density of a person is around that of water, 1 g/cm^3, so his mass is 120000 grams. Assuming the energy is equally distributed through the person's body, 44.7 ergs/sec is distributed throughout 120000 grams:

$$\begin{aligned} Dosage &= \frac{44.7\ ergs/sec}{120000 g}(3600 sec/hr) \\ &= 1.34 \frac{ergs/g}{hr} \end{aligned}$$

Since one REM equal 100 ergs/g for gamma radiation, we have

$$\begin{aligned} Dosage &= 1.34\frac{ergs/g}{hr}(\frac{1\ REM}{100\ ergs/g}) \\ &= 0.0134\frac{REM}{hr} \\ &= 13.4\frac{mREM}{hr} \end{aligned}$$

This is quite a bit of radiation, six times what it should be in a work area.

Natural Radiation

There are a few radioisotopes that exist in our environment. Isotopes that were present when the earth was formed and isotopes that are continuously produced by cosmic rays can exist today if they have long enough half-lives. Here we will discuss 5 of these isotopes. Four were produced when the earth was formed: K^{40} (half-life of 1.277 x 10^9 years), U^{238} (half-life of 4.51 x 10^9 years, Th^{232} (half-life of 1.4 x 10^{10} years), and U^{235} (half-life of 7.1 x 10^8 years). C^{14} (half-life 5280 years) is continuously produced in the upper atmosphere by cosmic rays entering the earth.

K^{40}

Most of the potassium found on earth is the stable K^{39}. However, a small fraction, 0.0117%, of all potassium is K^{40}. K^{40} is radioactive with a half-life of 1.277 x 10^9 years, and has the following decay scheme:

Figure of Decay scheme of K40

K^{40} has an 89.28% chance to undergo beta decay to the ground state of Ca^{40}, and a 10.72% chance to undergo electron capture to Ar^{40}. When electron capture occurs it is almost always to the excited state of Ar^{40}, 99.53% of the time. From the excited state, Ar^{40} decays to the ground state emitting a gamma particle with energy 1460.83 KeV. Thus when K^{40} decays, there is a 89.28% chance a beta particle is emitted and a $10.72(0.9953) = 10.67\%$ chance a gamma is emitted.

Although 0.0117% seems like a small amount, it means that one out of every 8500 potassium atoms is radioactive. This is a large amount! The average 70 Kg man has around 140 grams of potassium in his body. So the number of radioactive K^{40} nuclei in his body is:

$$Number\ of\ K^{40}\ nuclei = \frac{140g}{40g}(6.02x10^{23})(0.000117) = 2.47x10^{20} \qquad (3)$$

which is a lot of nuclei. The activity due of K^{40} decays in the average person can be calculated using the relation: activity $A = N\lambda$, or $A = N(ln2)/\tau$:

$$A = \frac{2.47x10^{20}ln(2)}{1.277x10^9(365)(24)(3600)sec} = 4240\frac{decays}{sec} \qquad (4)$$

This amount of activity is equal to $4240/37000 = 0.11$ μCi. Perhaps we should wear a radioactive sign around our necks! Fruits and vegetables can have as much as 0.4% potassium, and an average soil sample contains 2% potassium. Thus, one Kg of soil has an activity of 0.016 μCi due to the potassium content alone. By measuring the gamma spectrum of soil and food samples for long times, one or two hours, the potassium content can be measured to an accuracy of as good as 10%. K^{40} is the largest contributor to our natural background radiation.

U^{238}

Another isotope found in the earth is uranium 238. Due to its long half-life some still remains since the formation of the earth. U^{238} has a long decay series, undergoing alpha, beta and gamma decays until it finally becomes stable as lead 206, Pb^{206}. We list the complete U^{238} decay series:

Isotope	half-life	gamma energies
U^{238}	$4.468x10^9$ years	—-
Th^{234}	24.1 days	63.3 (4.47%)
		92.38 (2.60%)
		92.80 (2.56%)
$Pa^{234}m$	1.17 minutes	765 (0.207%)
		1001 (0.59%)
99.8% 0.13%		
Pa^{234}	6.75 hours	100 (50%)
		700 (24%)
		900 (70%)
U^{234}	$2.47x10^5$ years	53.2 (0.123%)
Th^{230}	$8.0x10^4$ years	67.7 (0.373%)
Ra^{226}	1602 years	186.2 (3.50%)
Rn^{222}	3.823 days	510 (0.076%)
Pc^{218}	3.05 minutes	——
99.98% 0.02%		
Pb^{214}	26.8 minutes	53.2 (1.1%)
		242.0 (7.46%)
		295.2 (19.2%)
		351.9 (37.1%)
		785.9 (1.09%)
At^{218}	2 seconds	——
Bi^{214}	19.7 minutes	609.3 (46.1%)
		768.4 (4.89%)
		806.2 (1.23%)
		934.1 (3.16%)
		1120.3 (15.0%)
		1238.1 (5.92%)
		1377.7 (4.02%)
		1408.0 (2.48%)
		1509.2 (2.19%)
		1764.5 (15.9%)
99.98% 0.02%		
Po^{214}	164 microsec	806.2 (1.23%)
		799 (0.014%)
Tl^{210}	1.3 minutes	296 (80%)
		795 (100%)
		1310 (21%)
Pb^{210}	21 years	46.5 (4.05%)
Bi^{210}	5.01 days	——
Po^{210}	138.4 days	803 (0.0011%)
Pb^{206}	Stable	

In the first column we list the isotopes in the decay series. If the decay is Alpha emission, the atomic number is lowered by 2 and the atomic mass is lowered by 4. For a Beta decay process, the atomic number increases by 1 and the atomic mass remains unchanged. In the middle column we list the half-life of the radioisotope shown in the first column.

In the last column we list the energy of the gamma rays emitted by the isotope in the first column. The number in parentheses is the yield percentage of the gamma. The isotopes in the series are called the daughter isotopes of U^{238}. From the table, one can see that as U^{238} decays via its daughter isotopes many alpha, beta and gamma particles are emitted.

Consider the following question: During the long decay series, how many of the various daughter isotopes are present at any one time? The half-lives are listed in the center column. Are there a smaller number of isotopes with short half-lives than isotopes with long half-lives at any particular moment? Any particular isotope will have a certain rate at which it is produced, and a rate at which it decays. Consider the situation in which isotope A decays to isotope B, which decays to isotope C. Let N_A be the number of nuclei of isotope A, N_B be the number of nuclei of isotope B, and N_C be the number of nuclei of isotope C. Let λ_A, λ_B, and λ_C be the corresponding decay constants for the decays. The rate at which the number of nuclei of isotope B decreases is $\lambda_B N_B$, which is just the decays/sec or the activity. The rate of formation of isotope B is just the decay rate of isotope A, $\lambda_A N_A$. So the change in the number of nuclei of isotope B per unit time is given by:

$$Change\ of\ N_B\ per\ unit\ time = +\lambda_A N_A - \lambda_B N_B \tag{5}$$

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B \tag{6}$$

This rate-of-change equation applies to every radioactive nucleus in the decay series. The first nucleus, U^{238}, will only have the decay term $-\lambda N$, and the final nucleus, Pb^{206}, will only have the rate of formation term, $+\lambda N$. The solution to the series of differential equations is complicated. However, if we observe the decay series after a long time, long enough for the series to come into equilibrium, then the solution is simple. After a long time, the number of radioactive nuclei of a particular isotope remains constant in time, $dN_B/dt = 0$. The rate of formation, $+\lambda_A N_A$, is equal to the rate of decay, $-\lambda_B N_B$:

$$\lambda_A N_A = \lambda_B N_B \tag{7}$$

for every isotope in the decay series. This equilibrium condition is referred to as secular equilibrium. Since λN is equal to the activity of an isotope, for secular equilibrium the activity of each isotope in the series is the same. In terms of the half-lives of the isotopes, we have:

$$\frac{N_A}{\tau_A} = \frac{N_B}{\tau_B} = \frac{N_C}{\tau_C} \tag{8}$$

Isotopes with longer half-lives have more nuclei at any particular time in the decay series than isotopes with shorter half-lives.

How much time is needed for the series to reach secular equilibrium? A solution of the coupled equations yields the result that after 5 or 6 half-lives of the longest lived isotopes in the series (not including the parent nucleus) the series is essentially at secular equilibrium. For the U^{238} series, U^{234} has the longest half-life of $2.47x10^5$ years. Since U^{238} was formed at a time much longer than this (at the earth's beginning), we can assume that today the U^{238} series is at secular equilibrium.

A good part of our natural background comes from the U^{238} decay series. One of the isotopes Rn^{222} is an inert gas. It can collect in rooms, and enter our lungs when we breath. When it decays, Pc^{218} is produced. Pc^{218} is not a gas, and can settle in the inner wall of the lungs. Having the remainder of the decay series take place inside the lungs can cause serious damage.

The largest peaks in the gamma spectrum from the U^{238} decay series are the 609 KeV (Bi^{214}), 352 KeV (Pb^{214}), 295 KeV (Pb^{214}) and 186 KeV (Ra^{226}). These peaks are easily identified in background spectra

Th^{232}

Another isotope that makes up part of our natural background is Th^{232}. Below we list the complete th^{232} decay series:

Isotope	half-life	gamma energies
Th^{232}	$1.405x10^{10}$ years	63.8 (0.267%)
Ra^{228}	6.7 years	——
Ac^{228}	6.13 hours	57.7 (0.487%) 99.5 (1.28%) 129.0 (2.42%) 154.0 (0.737%) 209.3 (3.88%) 270.2 (3.43%) 328.0 (2.95%) 338.3 (11.3%) 409.5 (1.94%) 463.0 (4.44%) 772 (1.50%) 794.9 (4.36%) 835.7 (1.61%) 911.2 (26.6%) 964.8 (5.11%) 969.0 (16.2%) 1588.2 (3.27%)
Th^{228}	1.91 years	84.4 (1.22%)
Ra^{224}	3.64 days	241.0 (3.97%)
Rn^{220}	55 seconds	550 (0.07%)
Po^{216}	0.15 seconds	——
Pb^{212}	10.64 hours	238.6 (43.6%) 300.0 (3.34%)
Bi^{212}	60.6 minutes	39.9 (1.1%) 727.3 (6.65%) 785.4 (1.72%) 1620.5 (2.32%)
64.06% 35.94% Po^{212} Tl^{208}	 304 nsec 3.1 minutes	 —— 277.4 (6.31%) 510.77 (22.6%) 583.2 (84.5%) 763.1 (1.81%) 860.6 (12.4%)
Pb^{208}	stable	

Since the longest half-life other than the parent nucleus (Th^{232}) is 6.7 years for Ra^{228}, the series is in secular equilibrium today. The largest gamma peak of 239 KeV from Pb^{212} is easily observable in the background of spectra taken over a long time (one hour or more).

U^{235}

A very small part of natural radiation is from the U^{235} decay series. U^{235} is found in ores with U^{238}. On the average 0.7% of the uranium in ores is U^{235}. We list the complete U^{235} decay series below:

Isotope	half-life	gamma energy (KeV)
U^{235}	$7.038x10^8$ years	143.8 (10.96%)
		163.33 (5.08%)
		185.7 (57.2%)
		205.3 (5.01%)
Th^{231}	25.5 hours	25.64 (14.5%)
		84.2 (6.6%)
Pa^{231}	$3.25x10^4$ years	27.4 (10.3%)
		300 (2.47%)
		303 (2.87%)
Ac^{227}	21.6 years	70 (0.08%)
98.6% 1.4%		
Th^{227}	1.82 days	50.1 (8.0%)
		236.0 (12.3%)
		256.3 (7.0%)
		300 (2.3%)
		329.9 (2.7%)
Fr^{223}	22 minutes	50.1 (36%)
		79.7 (9.1%)
		234.8 (3%)
Ra^{223}	11.43 days	144.2 (3.22%)
		154.2 (5.62%)
		158.6 (0.69%)
		269.5 (13.7%)
		323.9 (3.93%)
		338.3 (2.79%)
Rn^{219}	4 seconds	271.2 (10.8%)
		401.8 (6.37%)
Po^{215}	1.78 millisec	—
Pb^{211}	36.1 minutes	404.9 (3.78%)
		427.1 (1.75%)
		832.0 (3.52%)
Bi^{211}	2.15 minutes	351.1 (12.95%)
0.28% 99.7%		
Po^{211}	0.52 seconds	569.6 (0.0016%)
		897.8 (0.26%)
Tl^{207}	4.79 minutes	897 (0.16%)
Pb^{207}	stable	

The series is at secular equilibrium today, since the longest half-life of the isotopes in the series is $3.25x10^4$ years. U^{235} is an interesting isotope because of its fission properties. A single neutron can initiate fission. When U^{235} undergoes fission, it can release 3 neutrons. Each of these three neutrons can initiate another fission reaction, and a chain reaction can develop if the concentration of U235 is large enough. Because of its fission properties, U^{235} was the first radioisotope used for nuclear energy and weapons.

The peaks in the background gamma spectum due to U^{235} are small and difficult to observe. However, with the high resolution of a Ge detector, the three gammas emitted by U^{235}, at 185 KeV, 143 KeV can sometimes be seen in a uranium sample.

Below is a spectrum of background taken with our Ge detector for 4 hours. There are many peaks present, most of them come from K^{40}, the U^{238} series and the Th^{232} series.

Figure of complete spectrum of background radiation for a collection time of 4 hours.

Only the larger peaks are labeled, and the numbers above the peaks correspond to gamma rays from the Th^{232} and U^{238} decay series.