Nuclear Physics

size of atoms: take water (H_2O)

density = 1 gm/cc,

atomic weight = 18 gm/mole, (alternately, get mass of one molecule from mass spectrograph)

Avagadro's number = 6×10^{23}/mole

$(1\ \mathrm{cm}^3/\mathrm{gm})*(18\ \mathrm{gm/mole}) / (6\times10^{23}\mathrm{molecules/mole})$

$= 3 \times 10^{-23}\ \mathrm{cm}^3$/molecule, so

$$d_{atom} = V^{1/3} = 3 \times 10^{-8}\mathrm{cm} = \mathbf{3 \times 10^{-10}\ m}.$$

Nuclear Physics

size of **nucleus**: by Rutherford scattering,

$d_{nucleus}$ = **10^{-15} m** for light nucleus.

charge of nucleus: balances electronic

charges in atom, so = +integer number of e's

mass of nucleus: from mass spectrograph,

have mass as integer number of amu's, but mass # and charge # are not usually the same!

Nuclear Physics

Stability: see sheet detailing stable isotopes

Radiations:

1) α, β^-, β^+, γ are all emitted;
2) protons and neutrons are NOT emitted, except in the case of mass numbers 5 and 9;
3) alphas are emitted only for mass numbers greater than 209, except in the case of mass number 8.

Alpha (α) decay

example: $_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_{2}\alpha^{4} + \gamma$

(it is not obvious whether there is a gamma emitted; this must be looked up in each case) **Mass is reduced!**

NOTE: 1. **subscripts** must be conserved (conservation of **charge**) 92 = 90 + 2

2. **superscripts** must be conserved

(conservation of **mass**) 238 = 234 + 4

Beta minus (β^-) decay

example: $_6C^{14} \longrightarrow \; _7N^{14} + {}_{-1}\beta^0 + {}_0\bar{\upsilon}^0$

(a neutron turned into a proton by emitting an electron; however, one particle [the neutron] turned into two [the proton and the electron].

Charge and mass numbers are conserved, but since all three are fermions [spin 1/2 particles], **angular momentum, particle number, and energy are not**! **Need the anti-neutrino [$_0\bar{\upsilon}^0$] to balance everything**!

Positron (β^+) decay

example: $_6C^{11} \longrightarrow {}_5B^{11} + {}_{+1}\beta^0 + {}_0\upsilon^0$

(a proton turned into a neutron by emitting a positron; however, one particle [the proton] turned into two [the neutron and the positron].

Charge and mass numbers are conserved, but since all three are fermions [spin 1/2 particles], **angular momentum, particle number, and energy are not**! **Need the neutrino [$_0\upsilon^0$] to balance everything**!

Electron Capture

An alternative to positron emission is "Electron Capture". Instead of emitting a positron, some nuclei appear to absorb an electron and emit a gamma ray. The net result is the same: a proton is changed into a neutron and energy is released in the process.

Nuclear Physics

General Rules:

1) α emitted to reduce mass, only emitted if mass number above 209
2) β^- emitted to change neutron into proton, happens when have too many neutrons
3) β^+ emitted (or electron captured) to change proton into neutron, happens when have too few neutrons
4) γ emitted to conserve energy in reaction, may accompany α or β.

Mass Defect & Binding Energy

By **definition**, mass of $_6C^{12}$ is 12.00000 amu.

The mass of a **proton** (plus electron) is **1.00782** amu. (The mass of a proton by itself is 1.00728 amu, and the mass of an electron is 0.00055 amu.)

The mass of a **neutron** is **1.008665 amu**.

Note that $\mathbf{6*m_{proton+e} + 6*m_{neutron} > m_{C\text{-}12}}$.

Where did the missing mass go to?

Mass Defect & Binding Energy

Similar question: The energy of the electron in the hydrogen atom is -13.6 eV. Where did the 13.6 eV (amount from zero) go to in the hydrogen atom?

Answer: In the hydrogen atom, this energy (called the binding energy) was emitted when the electron "fell down" into its stable orbit around the proton.

Mass Defect & Binding Energy

Similarly, the missing mass was converted into energy (**$E=mc^2$**) and emitted when the carbon-12 atom was made from the six protons and six neutrons:

Δm $= 6 * m_{proton} + 6 * m_{neutron} - m_{C\text{-}12} =$

$6(1.00782 \text{ amu}) + 6(1.008665 \text{ amu}) - 12.00000 \text{ amu}$

$= .099$ amu; **$BE = \Delta m * c^2$** $=$

$(0.099 \text{ amu}) * (1.66 \times 10^{-27} \text{kg/amu}) * (3 \times 10^{8} \text{m/s})^2$

$= 1.478 \times 10^{-11} \text{J} * (1 \text{ eV}/1.6 \times 10^{-19} \text{J}) =$ **92.37 MeV**

Mass Defect & Binding Energy

For Carbon-12 we have:

BE = $\Delta m * c^2$ = 92.37 MeV

If we consider the binding energy per nucleon, we have for carbon-12:

BE/nucleon = 92.37 MeV /12 = **7.70 MeV/nucleon**

The largest BE/nucleon happens for the stable isotopes of iron (about 8.8 MeV/nucleon).

Rate of decay

From experiment, we find that the amount of decay of a radioactive material depends only on **two things**: **the amount of radioactive material** and the **type of radioactive material** (the particular isotope).

The rate of decay does **NOT** depend on temperature, pressure, chemical composition, etc.

Rate of decay

Mathematically, then, we have:

$$dN/dt = -\lambda * N$$

where λ **is a constant that depends on the particular isotope**, **N is the number of radioactive isotopes present**, and **the minus sign comes from the fact that dN/dt is DECREASING rather than growing**.

Rate of decay

We can solve this differential equation for $N(t)$: $dN/dt = -\lambda N$, or $dN/N = -\lambda\, dt$, or $\log (N/N_o) = -\lambda\, t$, or $\mathbf{N(t) = N_o\, e^{-\lambda t}}$.

Further, if we define activity, A, as

$\mathbf{A = -dN/dt}$ then $\mathbf{A} = \lambda N = \lambda N_o e^{-\lambda t} = \mathbf{A_o e^{-\lambda t}}$;

which means that **the activity decreases exponentially with time** also.

Half Life

$N(t) = N_o\, e^{-\lambda t}$ Does N(t) ever reach zero?

Mathematically, it just approaches zero. But in physics we have an integer number of radioactive isotopes, so we can either get down to 1 or 0, but not 1/2. Thus the above is really only an approximation of what actually happens.

Half Life

$N(t) = N_o\, e^{-\lambda t}$ The number of radioactive atoms does decrease with time. But is there **a definite time in which the number decreases by half**, regardless of what the beginning number is? YES:

$N(T\text{=half life}) = N_o/2 = N_o e^{-\lambda T}$, or $1/2 = e^{-\lambda T}$

or $-\lambda T = \ln(1/2) = \ln(1) - \ln(2) = 0 - \ln(2)$, or

$T(\text{half life}) = \ln(2) / \lambda$.

Half Life

Review: $\mathbf{N(t) = N_o\, e^{-\lambda t}}$

$\mathbf{A} = \lambda N = \mathbf{A_o e^{-\lambda t}}$

$\mathbf{T(half\ life) = ln(2) / \lambda}$.

We can **find T**(half life) if we can wait for N (or A) to decrease by half.

We can **find λ** by measuring N and A.

If we know either λ or T(half life), we can find the other.

Activity

Review: $N(t) = N_o\, e^{-\lambda t}$

$A = \lambda N = A_o e^{-\lambda t}$

T(half life) = ln(2) / λ .

If the half life is large, λ is small. This means that **if the radioactive isotope will last a long time, its activity will be small**; **if the half life is small, the activity will be large but only for a short time**!

Probability

Why do the radioactive isotopes decay in an exponential way?

We can explain this by using quantum mechanics and probability. Each radioactive atom has a certain probability (based on the quantum theory) of decaying in any particular time frame. This is explained more fully in the **computer homework** on Half-lives, **Vol 6, #4**.

Computer Homework

Computer Homework on Radiation Statistics, **Vol. 6, #3**, describes and then asks questions about how to deal with something that is probablistic in nature.

Computer Homework on Nuclear Decay, **Vol. 6, #5**, describes and then asks questions about the nuclear decay schemes we have just talked about.

Radioactivity around us

If radioactive atoms decay, why are there still radioactive atoms around?

Either they were made not too long ago, or their half-lives have to be very long compared to the age of the earth.

Let's see what there is around us, and then see what that implies.

Radioactivity around us

Carbon-14: Half life of 5,730 years.

In this case, we think that carbon-14 is made in the atmosphere by collisions of Nitrogen-14 with high speed cosmic neutrons: ${}_0n^1 + {}_7N^{14} \longrightarrow {}_1p^1 + {}_6C^{14}$.

We think that this process occurs at the same rate that C-14 decays, so that the ratio of C-14 to N-14 has remained about the same in the atmosphere over time.

Radioactivity around us

This is the **assumption** that permits carbon dating: plants take up carbon dioxide from the atmosphere, keep the carbon, and emit the oxygen.

When plants die, they no longer take up new carbon. Thus the proportion of carbon-14 to carbon 12 should decay over time. If we measure this proportion, we should be able to date how long the plant has been dead.

Radioactivity around us

Example of carbon dating:

The present day ratio of C-14 to C-12 in the atmosphere is **1.3×10^{-12}** . The half-life of C-14 is **5,730 years**. What is the activity of a 1 gm sample of carbon from a living plant?

A = λN = [ln(2)/5730 years]*[6×10^{23} atoms/mole * 1mole/12 grams * 1 gram]*[1.3×10^{-12}] = 7.86×10^{6}/yr = .249/sec = **15.0/min** .

Radioactivity around us

Thus, for one gram of carbon, $A_o = 15.0/\text{min}$.

If a 1 gram carbon sample from a dead plant has an activity of 9.0/min, then using:

$$\mathbf{A = A_o e^{-\lambda t}} \,,$$

we have $9.0/\text{min} = 15.0/\text{min} * e^{-(\ln 2/5730\text{yrs})t}$,

or $-(\ln 2/5730 \text{ yrs})*t = \ln(9/15)$, or

$t = 5730 \text{ years} * \ln(15/9) / \ln(2) =$ **4,200 years**.

Radioactivity around us

Another common element that has a radioactive isotope is potassium. About 0.012% of all potassium atoms are K-40 which is radioactive. (Both $_{19}K^{39}$ and $_{19}K^{41}$ are stable, and $_{18}Ar^{40}$ is stable.) Unlike carbon-14, we do not see any process that makes K-40, but we do note that **K-40 has a half life of about 1.3 billion years**.

Radioactivity around us

The activity of 1 gram of carbon due to C-14 was about .25/sec = .25 Bq.

The activity of 1 gram of K is: $A = \lambda N = [\ln(2)/1.26\text{x}10^9\text{yrs}]*[6\text{x}10^{23}/39]*[.00012]$

= 32/sec = 32 Bq.

[A decay/sec has the name Becquerel, Bq.]

(The half life of C-14 is smaller so the activity should be larger, but the ratio of C-14 to C-12 is also much smaller than K-40 to K-39/41 so the activity ends up smaller.)

Radioactivity around us

Another radioactive isotope found in dirt is $_{92}U^{238}$. Since it is well above the 209 mass limit, it gives rise to a whole series of radioactive isotopes with mass numbers **238, 234, 230, 226, 222, 218, 214, 210**. The **226** isotope is $_{88}Ra^{226}$, which is the isotope that Marie Curie isolated from uranium ore. The **222** isotope is $_{86}Rn^{222}$ which is a noble gas.

Radioactivity around us

The **U-238** itself has a half life of **4.5 billion years**. Thus, like potassium, the activity per gram will be fairly small.

The **Ra-226** (radium) has a half life of **1,600 years**, so that when it is isolated from the other decay products of the U-238, it will have a high activity per gram. This activity is called a Curie, and **1 Curie = 3.7×10^{10} Bq**.

Radioactivity around us

The $_{86}Rn^{222}$ (radon) has a half-life of **3.7 days**.

Because it's half life is so small, very little remains. But what little does, adds to our exposure. Since Radon is a noble gas, it bubbles to the surface and adds radioactivity to the air that we breathe.

Indoor air has something like a picoCurie per liter, with the exact amount depending on the soil, building materials and ventilation.

Radioactivity around us

Since high mass radioactive isotopes can only reduce their mass by four, there should be **four radioactive series**. **U-238 starts one of the four**. Although there are higher mass isotopes, like Pu-242, all these other isotopes have half lives much smaller than U-238's, and we don't see these existing on their own on the earth. (Pu-242 has a half life of 379,000 years.)

Radioactivity around us

The longest lived isotope in a **second series is 92-U-235**, which has a half life of **0.7 billion years**. It's half life is much smaller than U-238's, and there is only 0.7% of U-235 compared to 99.3% of U-238 in uranium ore. (Pu-239 has a half life of 24,360 yrs.)

The longest lived isotope in a **third series is 90-Th-232**, which has a half life of **13.9 billion years**.

Radioactivity around us

The longest lived isotope in **the fourth series is 93-Np-237** with a half life of **2.2 million years**. Note: **million NOT billion**. We do not find any of this atom or this series on the earth (unless we ourselves make it).

Together this data on half lives and abundance of elements provides evidence that is used to date the earth - to about 4.5 billion years old.

X-rays

How does an x-ray machine work?

We first **accelerate** electrons with a high voltage (several thousand volts). We then allow the high speed electrons to **smash** into a target. As the electrons slow down on collision, they can emit photons - via **photoelectric effect** or **Compton scattering**.

X-rays

However, the maximum energy of the electrons limits the maximum energy of any photon emitted. In general glancing collisions will give less than the full energy to any photons created. This gives rise to the continuous spectrum for x-ray production.

X-rays

If an electron knocks out an inner shell electron, then the atom will refill that missing electron via normal falling of electrons to lower levels. This provides a characteristic emission of photons that depends on the target material.

For the inner most shell, we can use a formula similar to the Bohr atom formula:

X-rays

$\mathbf{E_{ionization} = 13.6\ eV * (Z\text{-}1)^2}$ where the -1 comes from the other inner shell electron. If the electrons have this ionization energy, then they can knock out this inner electron, and we can see the characteristic spectrum for this target material.

For **iron** with Z=26, the ionization energy is:

$13.6\ eV * (26-1)^2 = 1e *$ **8,500 volts**.

X-rays

This process was used to actually correct the order of the periodic table of elements. The order was first created on the basis of mass, but since there are different isotopes with different masses for the same element, this method was not completely trustworthy. The method using x-rays did actually reverse the order of a couple of elements.

X-rays

Note: the gamma rays emitted in nuclear processes are NOT related to the electron orbits - they are energy emitted by the nucleus and not the atom.

X and γ ray penetration

High energy photons interact with material in three ways: the **photoelectric effect** (which dominates at low energies), **Compton scattering**, and **pair production** (which dominates at high energies).

But whether one photon interacts with one atom or not is a probabilistic event. This is similar to radioactive decay, and leads to a similar relation:

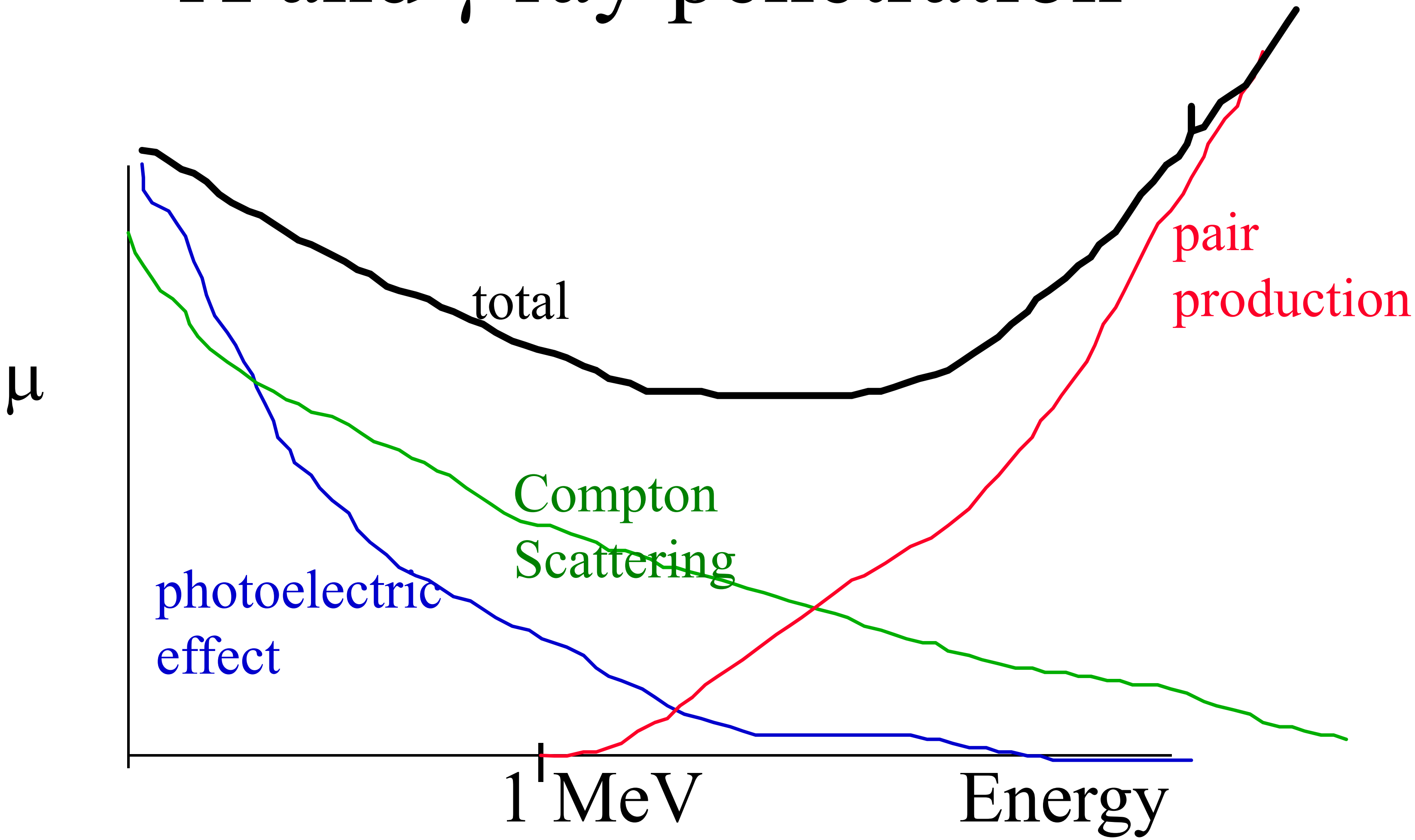
X and γ ray penetration

$I = I_o\, e^{-\mu x}$ where μ depends on the material the x-ray is going through.

In a similar way to half lives, we can define a half-value-layer, hvl, where **$hvl = \ln(2)/\mu$** .

Since the probability of hitting changes with energy, μ also depends on the energy of the x-ray as well as material.

X and γ ray penetration



Measuring Radioactivity

- How do we measure radioactivity?
- What is the source of the health effects of radiation?
- Can we devise a way to measure the health effects of radiation?

Measuring Radioactivity

- How do we measure radioactivity?

The Bq (dis/sec) and Curie (1 Ci = 3.7 x 10^{10} Bq) measure how many decays happen per time. However, different radioactive materials emit different particles with different energies.

- What is the source of the health effects of radiation?

Radiation (α, β, γ) ionizes atoms. Ionized atoms are important to biological function, and so radiation may interfere with biological functions.

- Can we devise a way to measure the health effects of radiation?

Measuring Health Effects

Can we devise a way to measure the health effects of radiation?

A unit that directly measures ionization is the **Roentgen (R) = (1/3) x 10^{-9} Coul created per cc of air at STP**. This uses air, since it is relatively easy to collect the charges due to ionization. It is harder to do in biological material, so this method is best used as a measure of **EXPOSURE dose**.

Measuring Health Effects

Can we devise a way to measure the health effects of radiation?

2. In addition to measuring ionization ability in air, we can also measure the energy that is absorbed by a biological material: **Rad = .01 J/kg**
MKS: Gray (Gy) = 1 J/kg = 100 rads.
This is called an **ABSORBED dose**.

Generally, one Roentgen of exposure will give one rad of absorption.

Measuring Health Effects

Can we devise a way to measure the health effects of radiation?

There is one more aspect of radiation damage to biological materials that is important - health effects depend on **how concentrated the damage is**.

Measuring Health Effects

Gamma rays (high energy photons) are very penetrating, and so generally spread out their ionizations (damage).

Beta rays (high speed electrons) are less penetrating, and so their ionizations are more concentrated.

Alphas (high speed helium nuclei) do not penetrate very far since their two positive charges interact strongly with the electrons of the atoms in the material through which they go.

Measuring Health Effects

This difference in penetrating ability (and localization of ionization) leads us to create an RBE (radiation biological equivalent) factor and a new unit: the rem. The more localized the ionization, the higher the RBE.

# of rems = RBE * # of rads . This is called an **EFFECTIVE dose**.

RBE for gammas = 1; RBE for betas = 1 to 2; RBE for alphas = 10 to 20.

Radiation Rates and Radiation Amounts

Note that **Activity** (in Bq or Ci) is a **rate**. It tells how fast something is decaying with respect to time.

Note that **Exposure**, **Absorption**, and **Effective doses** are all **amounts**. They do not tell how fast this is occurring with respect to time.

Levels of Radiation and Health Effects

To give some scale to the radiation levels in relation to their health effects, let's consider the "background" radiation.

Plants take up carbon, including radioactive carbon-14, from the air. Therefore, all the food we eat and even our bodies have carbon-14 and so are radioactive to some extent.

We need Potassium to live, and some of that potassium is K-40. This also contributes to our own radioactivity.

Levels of Radiation and Health Effects

In addition to our own radioactivity (and our food), we receive radiation from:

a) space in the form of gamma rays; the atmosphere does filter out a lot, but not all;

b) the ground, since the ground has uranium and thorium;

c) the air, since one of the decay products of uranium is radon, a noble gas. If the Uranium is near the surface, the radon will percolate up and enter the air.

Levels of Radiation and Health Effects

The amount of this background radiation varies by location. The **average** background radiation in the U.S. is around **200 millirems per year**.

This value provides us with at least one benchmark by which to judge the health effects of radiation.

Levels of Radiation and Measurable Health Effects

200 millirems/year: background

Here are some more benchmarks based on our experience with **acute** (short time) **doses**:

20,000 millirems: measurable transient blood changes;

150,000 millirems: acute radiation sickness;

200,000 millirems: death in some people;

350,000 millirems: death in 50% of people.

Low Level Effects of Radiation

The effects of low level radiation are hard to determine.

There are no directly measurable biological effects at the background level.

Long term effects of radiation may include heightened risk of cancer, but many different things have been related to long term heightened risk of cancer. Separating out the different effects and accounting for the different amounts of low level radiation make this very difficult to determine.

Low Level Effects of Radiation

At the cellular level, a dose of 100 millirems of ionizing radiation gives on average 1 "hit" on a cell. (So the background radiation gives about 2 hits per year to each cell.)

There are **five possible reactions** to a “hit”.

1. A "hit" on a cell can cause DNA damage that leads to cancer later in life.

Note: There are other causes of DNA damage, a relatively large amount from normal chemical reactions in metabolism.

Low Level Effects of Radiation

2. The body may be stimulated to produce de-toxifying agents, reducing the damage done by the chemical reactions of metabolism.
3. The body may be stimulated to initiate damage repair mechanisms.

Low Level Effects of Radiation

4. The cells may kill themselves (and remove the cancer risk) by a process called apoptosis, or programmed cell death (a regular process that happens when the cell determines that things are not right).
5. The body may be stimulated to provide an immune response that entails actively searching for defective cells - whether the damage was done by the radiation or by other means.

Low Level Effects of Radiation

There are two main theories:

1. **Linear Hypothesis**: A single radiation "hit" may induce a cancer. Therefore, the best amount of radiation is zero, and any radiation is dangerous. The more radiation, the more the danger.

This says effect #1 is always more important than effects 2-5.

Low Level Effects of Radiation

2. **Hormesis Hypothesis**: A small amount of radiation is actually good, but a large amount of radiation is certainly bad.

Many chemicals behave this way - for example B vitamins: we need some to live, but too much is toxic. Vaccines are also this way: we make ourselves a little sick to build up our defenses against major illnesses.

This theory says that at low levels, effects 2-5 are more important than effect 1.

Radiation Treatments

If high doses of radiation do bad things to biological systems, can radiation be used as a treatment?

Ask yourself this: does a knife do harm to biological systems? If if does, why do surgeons use scalpels?

Fast growing cancer cells are more susceptible to damage from radiation than normal cells. For cancer treatment, localized (not whole-body) doses regularly exceed 10,000,000 mrems.