6 RADIATION BASICS

Radiation comes in the form of particles or electromagnetic (EM) waves or both. Very small particles sometimes act like waves, and EM waves sometimes act like particles, so we sometimes call them wavicles. The most commonly known types of radiation are visible light photons and radio waves. But there are many more kinds of radiation:

Alpha particles	Helium nucleus (two neutrons and two protons)
Beta particles	electron
	Proton (Hydrogen nucleus)
	Neutron
	Larger ionic nuclei e.g., C, Fe, ...
Radio	EM wavicles
Microwave	EM wavicles
Infra-red	EM wavicles
Visible light	EM wavicles
Ultraviolet	EM wavicles
X rays	EM wavicles
Gamma	EM wavicles

This is not a complete list, nor are they in strict order of energy. All of these radiations can be harmful or helpful, depending on how they are used. Visible light and microwave ovens are very useful, but a laser can blind you or cut steel, and a microwaves can kill your small dog if you try to use them to dry the dog after a shampoo. Americium-241 gives off alpha and beta particles and gamma wavicles, but it saves lives in smoke detectors. Alpha radiation can light up a watch dial and is not able to penetrate skin or a sheet of paper, but you wouldn't want it in your lungs, where radon gas delivers it. Nuclear reactors can power a nation (e.g. France) or make a very expensive mess.

I want to point out some of the worst industrial accidents in history[1] (the top six according to one source[2]). Clearly, the top two were rated high for either cost or social perception, rather than the loss of life. I added the bottom four because they are well known diasters that killed many people.

DISASTER NAME	YEAR	FATALITIES
1. The Chernobyl disaster, Ukraine	1986	43
2. The Deepwater Horizon, USA	2010	11
3. Bhopal accident, India	1984	3,787
4. Benxihu Colliery (mine), China	1942	1,549
5. Courrières mine, France	1906	1,099
6. Oppau explosion, Germany	1921	600

[1] A complete list of multiply-fatal industrial accidents would be vastly longer, but would have no nuclear power reactors outside of the former USSR.

[2] https://news.gminternational.com/industrial-safety-top-6-worst-accidents-in-history

7. Honkeiko mine, China (under Japanese control)	1942	1549
8. Rana Plaza Collapse, Bangladesh	2013	1100
9. Monongah mine, West Virginia	1907	350
10. Triangle Shirtwaist Factory, NY, USA	1911	<150

Note that the following nuclear accidents that some people consider to be disasters didn't kill anyone:

Three-Mile Island, USA	1979	0
Fukushima, Japan	2011	0

They just made an expensive mess and created jobs. Some 2,000 people died from being forcibly relocated due to the Fukushima tsunami, but no one, not even workers, died from radiation[3]. Only the Russians have managed to kill people from radiation at a nuclear power reactor.

But careless handling of radiation can kill, and here's how. Particles and wavicles have energy that they can transfer to other particles in living organisms. When radiation enters a living organism like plants or humans, the photons and particles tend to collide with electrons much more often than they collide with nuclei. This creates an ion, a charged molecule that is missing an electron (the molecule is also a free radical). This modified ionic molecule is very reactive and unstable, so it reacts almost instantly with whatever other molecule is nearby. The result is a huge number of changed molecules, some of them in a highly ordered DNA polymer. An error in the cells gene sequence. A mutation.

[3] One Fukushima worker died of lung cancer 7 years after the Fukushima disaster.

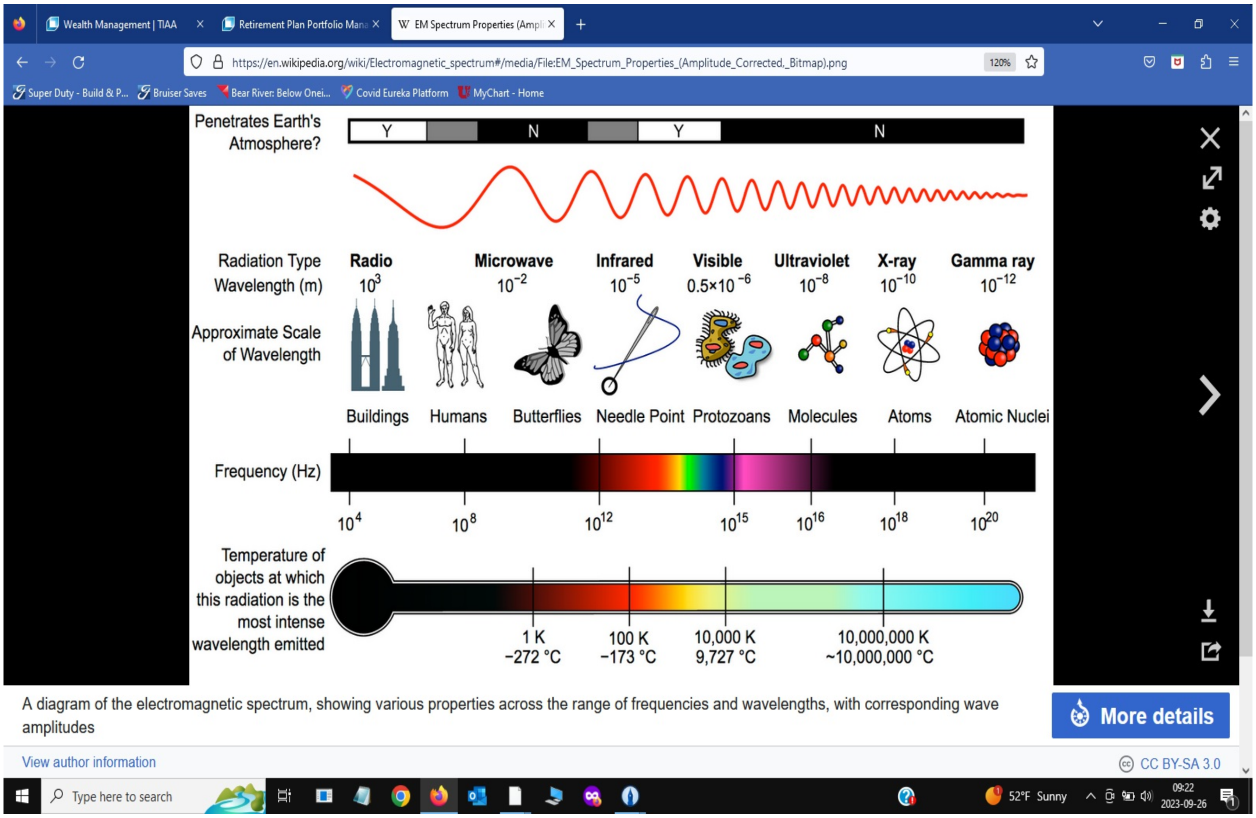

Figure 1 Electromagnetic spectrum. (Chart omits particles larger than electrons and includes only waves).

But living cells and DNA and radiation have been around for billions of years, and the cells have evolved repair enzymes to correct DNA damaged by radiation. So we survive lots of mutations and cancers every day of our lives. Sometimes the error doesn't get fixed, so the cell fails to work properly, and self destructs. Or the cell begins to replicate itself and becomes cancer. Then we use radiation and toxic chemicals to kill the cancer cells.

There is a significant difference between X rays and Ultraviolet radiation: X rays have enough energy to knock electrons out of atoms and molecules; Ultraviolet UVB radiation does not. Removing an electron leaves a free radical positive ion in place of a neutral molecule in, e.g., a DNA helix. And that loose electron can knock other electrons free of their atoms, which creates more free radicals. Free electrons eventually find orbits around other atoms, thereby creating different ionic free radicals. Ultraviolet radiation (and visible light, and infrared light, and microwaves, and radio waves) lack the energy to knock an electron completely free of its nucleus. So when we speak of radiation, what we often mean is Ionizing Radiation, the kind of radiation that can cause mutations and cancer: X rays and gamma rays and fast moving particles with 5 electron volts (eV) to several million eV and cosmic particles up to 10^{20} eV.

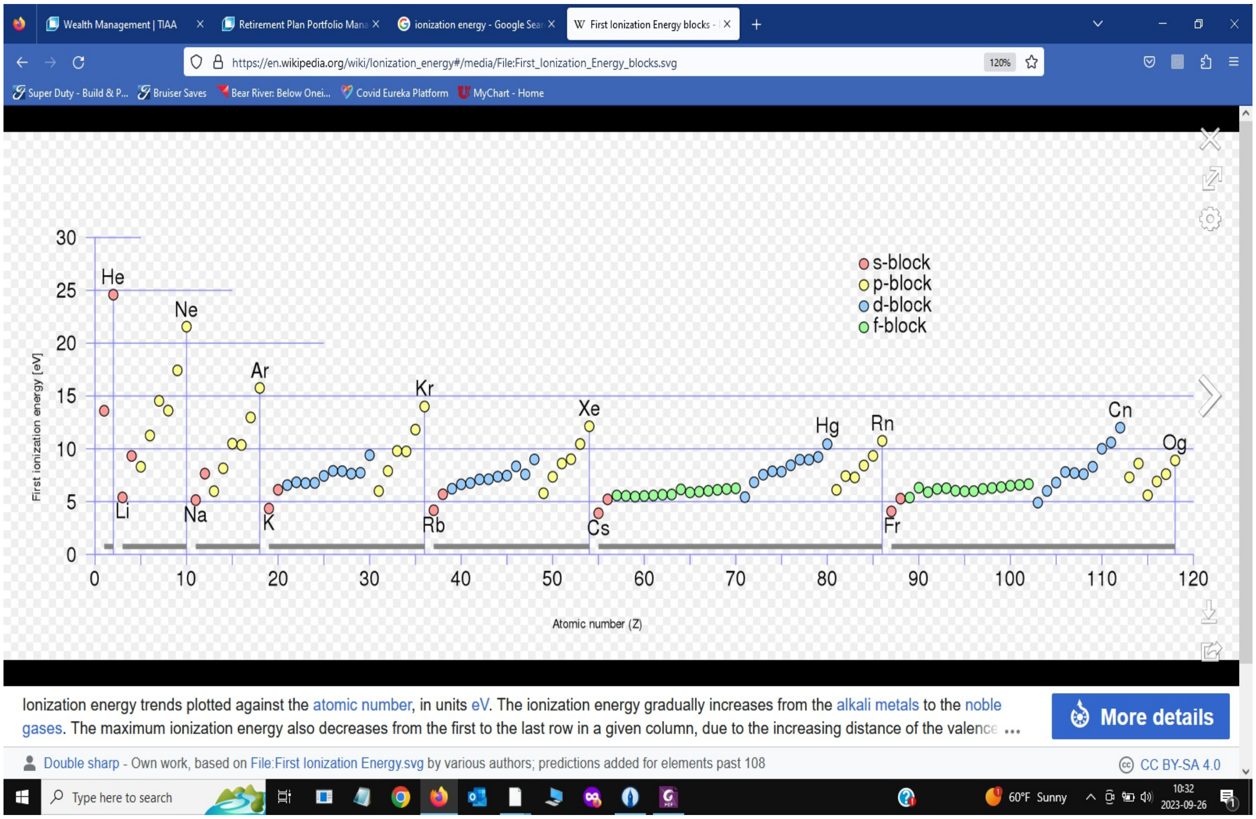

Figure 2 Energy required to ionize (free an electron from) each atom.

In summary, the characteristic that makes Ionizing Radiation dangerous[4] is its ability to deliver a packet of sufficient energy (>5 eV) directly to single electrons, thereby creating free radical ions in the operational molecules of living cells. Damage to proteins, lipids, and carbohydrates, reduces a cells efficiency until the damage can be repaired; but damage to DNA can permanently impair the cells ability to repair and replace itself accurately. So DNA damage at least makes the cell function less efficiently, or kills the cell, or makes a damaged cell immortal. Our cells receive and correct around 50,000 DNA damages per cell per day. Most of these damages are caused by our own oxygen-powered metabolism, and are promptly corrected..

It requires multiple mutations to create an immortal cell (a cancer cell). That's why we often say that it takes 20 years to create a cancer. One of the ways these multiple mutations can occur is by sustaining damage to the genes for one of the DNA repair mechanisms, so that DNA repairs cause mutations, instead of repairing them.

How much damage can one weightless photon do? Let's calculate the energy in an ionizing photon like an extremely high frequency UVB photon[5], then find how many free electrons could

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[4] Some chemicals also cause damage to DNA that may result in immortal cells

[5] UVC includes a wide range of frequencies which are considered to be ionizing. UVC photons can eject an electron from its nucleus. *{Many UVB and UVC photons have enough*

be created from that energy[6]. Assume one ion radical and one free electron are created from the first collision, thereby using up some of the collision's energy. Then the freed electron carries the remaining energy to subsequent collisions. For every subsequent collision, assume that the incoming electron gives all extra energy to the freed target electron[7]. Assume that each freed electron requires 5eV of energy (see the preceding chart of ionization potentials showing that most atoms have potentials between 5 and 10 eV). Apply Planck's equation stating that photon energy is equal to photon frequency times Planck's constant.

$$E = hv$$

(The energy of a wavicle equals Planck constant times the wave frequency.)

5 eV is >= the ionization energy for most elements.

$1.1*10^{15}$ = max frequency v in UVB range

E in Joules = h Joule seconds times v Hz per second

$E = 6.63*10^{-34}$ J s $* 1.1*10^{15}$ s^{-1} $= 7.1*10^{-19}$ Joules

$E = 7.1*10^{-19}$ J

E in Joules $* 6.24*10^{18}$ eV/J = 4.4 eV

4.4 eV / 5 eV per radical = **0 IonRadical pairs per incoming photon**

I conclude that UVB cannot free an electron from its nucleus, cannot produce a free radical, and cannot directly induce mutations in DNA by ionization. However, it is known that UVB can cause cyclobutane pyrimidine dimers (CPDs), which can indirectly cause DNA double strand breaks (DSBs). DSBs can lead to cell death, mutations, and cancer. However, CPDs have been routinely repaired for 2-3 billion years in all living cells.

A similar calculation for a typical diagnostic X ray, assuming the same resolution as my 4k UHD Nikon camera (8 megapixels = 8megabits = $8x10^6$ photons for black and white Xray image) yields a very different answer:

Typical frequency for diagnostic X ray = 10^{17} Hz

$6.63x10^{-34} * 10^{17}$ gives us $6.6x10^{-17}$ J $* 6.24x10^{18}$ eV/J = 414 eV

414 eV / 15 eV / ion pair = 27 ion pairs created per X ray photon

Assume that every photon that doesn't hit bone passes through to expose the film.

Assume that bone covers half of the image and absorbs all photons that strike it.

$4x10^6$ photons * 27 ion radicals per photon = **1.6 Billion ion radicals per X ray film**

My simplifying assumptions have no doubt led to an underestimate of the total number of photons and radicals per film. Most of the damage that occurs is to proteins, carbohydrates, lipids, and electrolytes, but a small fraction of a billion is still a big number. Then there all the free radicals that we generate each day just by using oxygen in our cells. Be thankful for all

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energy to cause dimerization of sequential pyrimidine bases (thymine and cytosine) in DNA. Such damage is routinely repaired by multiple biochemical mechanisms}.

[6] Normally, UVC is completely blocked by ozone in our atmosphere, and does not reach us.

[7] The assumption implies that the incoming electron then replaces the target electron, so there is no accumulation of free electrons that we're not counting.

those DNA repair mechanisms that I mentioned earlier. **We survive 10,000 to 100,000 DNA ionizations per cell per day**.

Sketch your own image of an Ionizing Radiation colliding with a DNA electron. Choose your radiation from the list of Ionizing Radiations.
Briefly tell me why ionizing radiation is dangerous, and non-ionizing radiation is normally not dangerous.

HOMEWORK

1 What is the smallest part of a chromosome that ionizing radiation can damage to cause a mutation?.
2 Is that mutation likely to cause cancer?
3 Arrange the following in order of increasing energy: xrays, UVA, UVC, gamma, radio
4 Which of the radiations above are ionizing?
5 Name three particulate radiations:
6 How likely is it that you or someone you know will die from radiation from a nuclear power plant?
7 How likely is it that anyone will die from radiation from a nuclear power plant, excluding russian built plants?
8 Can a photon with no mass at all impart momentum and kinetic energy to an electron?
9 What does such an interaction create?