Effects of radiation on living organisms

1. Background

The term *radiation* is elastic. Unfortunately it has come to mean “something terrible[1]” in ordinary conversation. Literally radiation means “anything emitted from a localized source”, but in the context of biology we mean something quite specific. Human beings live amidst a sea of radiation of all sorts. It is useful to classify these radiations according to their biological effects, especially on human beings.

Since the early part of this century we have been aware that all radiation, including electromagnetic fields, consists of particles. The more energy the particles of radiation transmit to living cells, the more they can affect them. We classify radiation according to increasing energy per particle because this is the same as listing them according to increasing harmfulness. We generally classify radiation as “penetrating” or “non-penetrating”: penetrating means radiation such as *x*-rays, that pass through our skin, whereas non-penetrating radiation stops at our skin.

Types of radiation

Electromagnetic spectrum		
nonpenetrating, non-bioactive	low frequency	magnetic fields, power lines
	radio	AM, FM radio;
	infrared	Heat lamps, radiant heaters, wood stoves
nonpenetrating, bioactive	ultraviolet	UV tanning lights, sunlight
Penetrating, bioactive	*x*-rays	medical, dental *x*-ray machines; TV & computer cathode ray tubes
	γ-rays	radioactive decays, cosmic rays
Nuclear and particle spectrum		
Penetrating, very bioactive	α-particles	nuclei of helium atoms, emitted mainly in radioactive decays of heavy elements (uranium, radium, radon)
	β-particles	electrons, emitted in radioactive decays of various isotopes (such as ^{40}K); also produced in electron accelerators
	neutrons	produced mainly in nuclear explosions and nuclear reactors
Very penetrating, bioactive	Cosmic ray protons and shower particles	ultra-high energy protons from outer space collide with atoms in the upper atmosphere to shower us with leptons, γ-rays and mesons; there is no way to shield against them except in the deepest mines.

1. …in the sense of *terrifying*, as in “Ivan, the Terrible”.

In medicine, energy at radio frequencies can be used to produce local heating in tissues—at low intensities this is called diathermy. At high intensities and higher frequencies, this effect is applied in surgery to excise tissue while cauterizing it. The *RF curette* is the instrument of choice for operations in heavily vascularized areas of the body, such as the scalp and prostate glands. Bowel polyps can be easily excised with minimal blood loss using a similar instrument that can be passed through a colonoscope.

Microwave ovens emit radio waves at wavelengths especially absorbed by water molecules. The molecules absorb energy and become hot, thereby cooking the food. As far as hazard to life and limb is concerned, a leaky microwave oven can give you ordinary burns from too much heat.

Powerful radar systems can kill at short ranges—basically, the organism absorbs too much power. They are also known to stimulate cataracts in the lenses of mammalian eyes. That is, it is definitely a bad idea to work near radar antennas when they are in operation.

Certain authors find it both profitable and enjoyable to frighten the American public with technological bogey-men. One such has claimed both that microwave ovens pose an unacceptable health risk to their users and that there exists a vast conspiracy (involving among others the US Government) to cover up these facts[2].

Similar claims of hazard have been advanced (by the same author—surprise!) regarding the deleterious effects of the electric and magnetic fields of power lines[3].

2. Effects of penetrating radiations

In this chapter we discuss the effects of penetrating radiation on living cells and complex organisms. We begin with the electromagnetic spectrum. Our eyes detect electromagnetic waves in the wavelength region 4000 Å (violet) to 7000 Å (red), *i.e.* the range is $4\text{–}7\times10^{-5}$ cm. The energy range of the corresponding photons is 3.1-1.8 electron volts[4], according to the Planck-Einstein relation

$$E = h\nu .$$

That is, the energy of visible-light photons is sufficiently great to excite atoms and molecules, or to break the weaker types of chemical bond (for example the hydrogen bond whose typical strength is 0.2 eV). However, most matter is opaque to radiation in the visible range, so these photons neither penetrate past our skins nor influence our internal body chemistry[5] (except through the eyes, of course).

2. Paul Brodeur, *The Zapping of America: microwaves, their deadly risk, and the coverup* (Norton, New York, 1977).

3. Paul Brodeur, *Currents of death: power lines, computer terminals, and the attempt to cover up their threat to your health* (Simon and Schuster, New York, 1989); *The great power-line cover-up: how the utilities and the government are trying to hide the cancer hazard posed by electromagnetic fields* (Little, Brown and Co., Boston, 1993). See the Web site *http://www.phys.virginia.edu/classes/304/electrophobia/em_fld.htm* for a more complete discussion of this.

4. An electron volt is a unit of energy equal to the energy gained by an object with the charge of an electron, falling through an electrostatic potential of one volt. Since the electron's charge is (in magnitude) 1.6×10^{-19} Coulombs, $1\text{eV} = 1.6\times10^{-19}$ Joule.

5. Visible light photons are the primary energy source in plant photosynthesis. The chlorophyll molecule is specifically evolved to capture visible light, converting it into chemical energy that is then used to promote the synthesis of energy-rich carbohydrate molecules. See, *e.g.*, Xiche Hu and Klaus Schulten, "How Nature Harvests Sunlight", *Physics Today* (Aug 1977) p. 28ff.

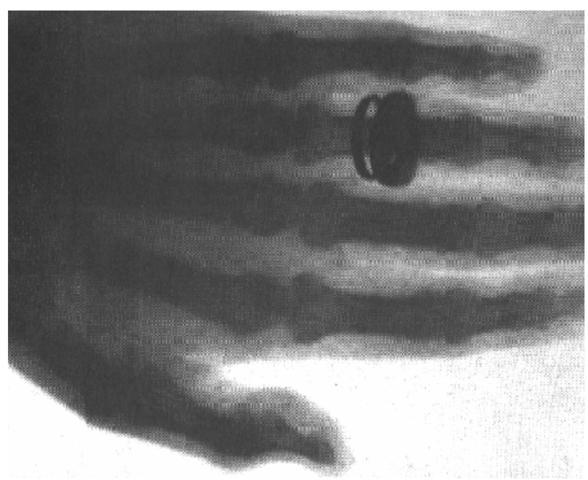
Next in order of particle energy are ultraviolet (UV) photons, with wavelengths[6] in the range 100 to 4000 Å, and energies ranging from 4 to 124 eV. These penetrate into the skin where they can cause damaging chemical reactions whose effects can include sunburn or skin cancer. The skin pigment melanin is manufactured by skin cells precisely to prevent UV rays from penetrating the epidermal layer to the basal skin cells.

However some UV must penetrate to the basal cells in order to convert lipids into Vitamin D, vital to calcium utilization. Thus humans adapted to high latitudes tend to produce less melanin (*i.e.* to be less pigmented) than humans adapted to equatorial life, because the reduced intensity of solar UV at high latitudes would produce insufficient Vitamin D. (In fact, people living at the most northerly latitudes—Scandinavia, Greenland and Alaska—historically depended on oily fish such as salmon and cod, which happen to be rich in Vitamin D.

X rays were discovered by Wilhelm Conrad Roentgen in 1895. Almost immediately he realized that they could penetrate solid matter and produce a shadow image on photographic film, as shown to the right (it is Frau Professor Roentgen's hand, showing her finger bones and her ring.). Within a few years X ray machines were ubiquitous in medical diagnostic practice throughout the civilized world. Soon practitioners began to discover that unlimited exposure to X rays was unwise. They began to report skin burns and lesions that took a long time to heal, comparable to ordinary burns although without the immediate pain that characterizes a thermal burn.

The discovery of natural radioactivity (Antoine Henri Becquerel, 1896)—spontaneous release of invisible, penetrating rays from uranium salts, that could fog a photographic film through its light-proof wrapper—began a new era. Soon it was realized[7] that these radiations were of three distinct types. Further work revealed that most of the mass of the atom is concentrated in its *nucleus*, that radioactivity represented transformations of atomic nuclei, and that the three types of radiation (called α, β and γ) consisted respectively of energetic helium nuclei, energetic electrons and photons (that is, electromagnetic quanta) of unprecedentedly short wavelength.

In addition to nuclear radiation—whether natural or from artificially produced radioactive nuclides—we also consider high energy particles produced in particle accelerators as well as those which impinge on the Earth from outer space, called *cosmic rays*. The so-called primary cosmic rays consist mainly of extremely energetic hydrogen nuclei (protons). When these collide with atomic nuclei in the upper atmosphere they produce showers of various sorts of particles, of which the longest-lived (and therefore the most prevalent at the sea level) are *muons*[8]. Cosmic rays can have energies up to 10^{22} eV, although the vast



6. The boundary between "soft" X-rays and "hard" ultraviolet rays is not well defined.
7. See, *e.g.*, A. Pais, *Inward Bound* (Oxford University Press, New York, 1986) for a discussion of these discoveries.
8. Muons are particles whose rest-mass is about 200 times greater than that of the electron, but which in all

majority of those reaching the Earth's surface have energies in the range 1-2 GeV[9].

3. Passage of radiation through matter

On passing through matter the various types of penetrating radiation lose energy in different ways. Alpha particles lose energy by colliding with atomic electrons, thereby giving them sufficient energy to break away from the atoms they were attached to. This process is called *ionization* since it produces a trail of ions and free electrons in the α particle's wake. Since electrons are about 8000 times lighter than α's, the effect is rather like that of a bowling ball colliding with a cloud of ping-pong balls. The latter are accelerated in profusion whereas the bowling ball hardly notices the ping-pong balls. A similar process occurs when an energetic proton passes through matter, although it produces less ionization per unit distance because it has half the charge and one fourth the mass of the α particle. Shown below are graphs of range *vs.* energy for alpha particles and protons in air.

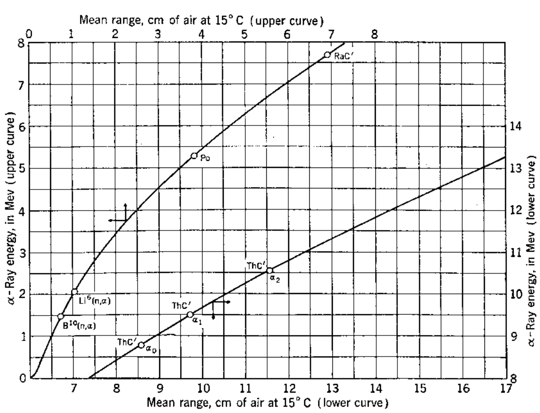


Fig. 3.2 Range-energy relationship for α rays in dry air at 15°C and 760 mm Hg. The curves agree with those of Bethe (B44) and with the tables by Jesse and Sadauskis (J12). Two low-energy calibration points (J12) are provided by the α rays emitted in the thermal neutron reactions $B^{10}(n,\alpha)Li^7$ and $Li^6(n,\alpha)H^3$.

Although the theoretical description of the passage of energetic charged particles such as protons or α's was once considered rather difficult, it is now

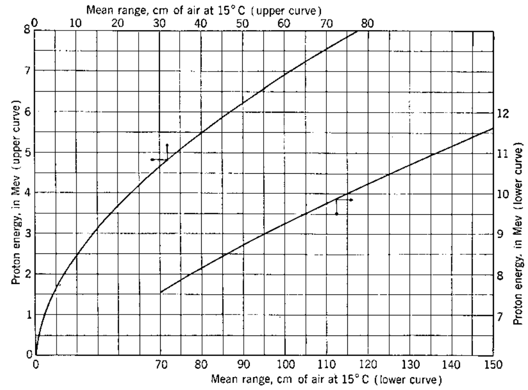
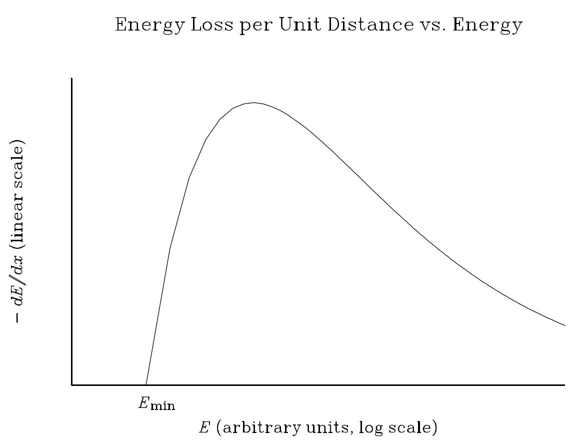


Fig. 3.3 Range-energy relationship for protons in dry air at 15°C and 760 mm Hg. [*From Bethe* (B44).]

a standard exercise in introductory courses in quantum mechanics. The rate at which a (nonrelativistic) ion of charge $+ze$ and kinetic energy E loses energy in matter (*linear energy transfer* or LET) is given by

$$\frac{dE}{dx} = -4\pi n Z \frac{M z^2 e^4}{m_e E} \ln\left(\frac{4 m_e E}{M I_{av}}\right) ,$$

where n is the atom number-density, Z the atomic number, I_{av} the average ionization energy and m_e the electron mass. As we can see from the graph below, there is no energy loss once the incident



their other physical properties are strikingly similar to electrons. That is, they are a sort of heavy electron.

9. A GeV (*giga*-electron volt) is a unit of 10^9 eV.

energy falls below that needed to produce ionization[10]. The energy loss per unit path length also falls to zero with increasing kinetic energy. Thus there is a broad maximum where the rate of energy loss per unit distance is roughly constant. Let us estimate, from the formula given above, the LET for 5 MeV α particles passing through water. The ionization energy of hydrogen is 13.6 eV and that of oxygen is—say—100 eV. The coefficient in front of the logarithm is about 5×10^7 eV/cm, and the logarithmic term (weighted for the numbers of electrons pertaining to hydrogen and oxygen atoms)

$$2\ln\left(\frac{E}{2.7\times10^4}\right) + 8\ln\left(\frac{E}{2\times10^5}\right) = 36$$

at $E = 5$ MeV, giving an LET of something like 20 eV/Å, a tremendous rate of energy loss. We may conclude that α particles from radioactive nuclei do not travel further than a few microns in matter as dense as living tissue.

In fact, this is at best a rough estimate of the range, since the rate of energy loss decreases rapidly as the energy falls. Since most of the stopping was the result of the oxygen, we can approximate the range in water by appropriately scaling the result for air, shown empirically above. The density of oxygen atoms in water is about 4,000 times that of air (regarding N_2 as the same as O_2 for this purpose). Thus we estimate the range of 5 MeV a particles in living tissue as

$$R \approx \frac{3.5\,\text{cm}}{4\times10^3} \approx 10\,\mu\,.$$

This is about the thickness of a typical cell. In other words, keeping an α emitting radioactive source in one's pocket, as early experimenters were wont to do, can lead to skin burns (if the source is intense) and possibly to skin cancer (if the exposure is prolonged) but not to internal damage.

We note that a scaling relation applies to other charged particles:

$$R\left(m_1, z_1, E_1\right) \approx \frac{m_1 z_2^2}{m_2 z_1^2} R\left(m_2, z_2, \frac{m_2}{m_1} E_2\right).$$

Thus, for example, protons of kinetic energy 3 MeV should have a range about that of α particles of kinetic energy 12 MeV, all else being equal. As the graph below shows, the range of 4 MeV protons in air is about 15 cm, cofortably close to the 14.5 cm for 12 MeV α's.

Next we consider the stopping of β rays (electrons). The major differences between them and heavier charged particles (such as protons or α's) are first, since their kinetic energies are typically larger than their rest mass (that is, in energy terms $m_e c^2 = 0.511$ MeV whereas β ray energies often exceed 1 MeV) their velocities are close to the speed of light. Second, their masses are the same as the particles (atomic electrons) they collide with, hence they lose a larger fraction of their energy with each collision than protons or α's do. For example, a 5 MeV proton has a momentum of 100 MeV/c whereas the momentum of a 5 MeV electron is only 5.4 MeV/c.

The effect of decreased inertia and the effect of relativistic velocity conflict—a 10 MeV electron has little inertia, but also creates little ionization. Its range in water would be of order 10 cm. To put it another way, typical fast electrons emitted in nuclear decays are far more penetrating than α particles but do far less damage per unit distance along their stopping track.

Finally we discuss γ rays, energetic photons. Their absorption by matter takes place by several (domi-

10. This is not strictly true—the moving particle can lose energy by exciting atoms into bound excited states, but this is approximately taken into account by the choice of average ionization energy.

nant) mechanisms. First, a photon can be absorbed on a bound electron, knocking it loose from the atom—the photoelectric effect. Second, a photon can scatter elastically from an electron, losing some energy in the process (since the initial electron is nearly at rest whereas the final one may have considerable kinetic energy). This is called Compton scattering. Finally, a photon whose energy exceeds the threshold

$$E_\gamma(\text{min}) = 2m_e c^2 = 1.02 \text{ MeV}$$

can produce an electron-positron pair ("pair production") with the necessary momentum[11] being supplied by a heavy nucleus. In a diagram where a photon is absorbed on (or emitted from) an electron, a factor of the electron charge e must be present in the corresponding probability amplitude. Thus the cross section for Compton scattering has a factor

$$Z e^4 = \frac{Z}{(137)^2}$$

(in dimensionless units), whereas the photoelectric cross section has only a factor

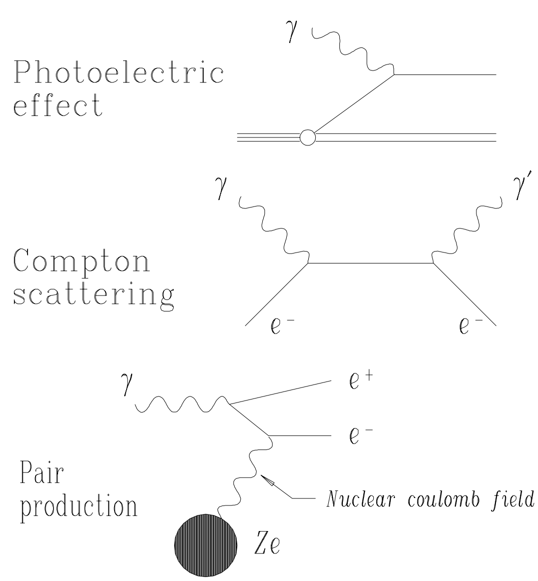
$$Z e^2 = \frac{Z}{137}.$$

(The factor Z in either case accounts for the number of electrons per atom.)

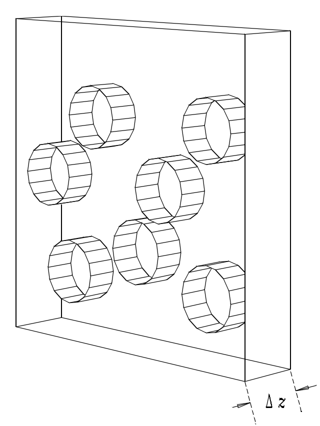
The pair production amplitude has a factor

$$\left(Ze\, e^2\right)^2 = \frac{Z^2}{(137)^3}$$

which might seem, at first glance, smaller than the Compton cross section, even if the nucleus is lead ($Z = 82$) or uranium ($Z = 92$). The Compton process in turn might seem smaller (by a factor $1/137$) than the photoelectric cross section. However,



because there are additional factors (such as the electron momentum distribution in the atom, or the final-state phase space) that enter the calculation, one finds that photoabsorption dominates the total absorption for low energy photons, the Compton process dominates the intermediate range, and pair production becomes dominant at higher energies. Clearly the effects of pair production should show up at lower energies in materials



Schematic representation of cross sections

11. It is straightforward to show that the process $\gamma \rightarrow e^+ e^-$ cannot take place in vacuum because energy and momentum cannot be conserved simultaneously. But if one of the outgoing charged particles can exchange momentum with a heavy nucleus (by scattering in its Coulomb potential) the conservation laws can be maintained.

of increasing atomic number. This is shown for photoabsorption in water and in lead in the figures to the right.

4. Attenuation of radiation in matter

Since nuclear radiations lose energy on passing through matter, their intensity may also be expected to be attenuated. That is, the more matter is in the way, the less radiation gets through. This is the idea behind *shielding*.

Consider a thin slice of matter, of area A and thickness Δx. It contains, on average,

$$\Delta N = nA\Delta x$$

atoms. If each atom can be thought of as having a cross-sectional area σ and if the slab is sufficiently thin that none of the areas overlap, then of Kparticles that fall at random on the area A, on the average

$$\Delta K = K\frac{\sigma\,\Delta N}{A} \equiv K\,n\sigma\,\Delta x$$

will be scattered or absorbed, or otherwise removed from the beam. That is, the probability of absorption, per particle, is $\lambda\,\Delta x$. This is illustrated graphically in the top illustration on the next page.

We can discuss the removal of particles from the beam in terms of probabilities: let $p_k(x)$ be the probability that at position ξ there are k particles. It is now easily seen that the probability to have k at $x + \Delta x$ is given by

$$p_k(x + \Delta x) = p_k(x)\left(1 - \beta_k\right) + p_{k+1}(x)\,\beta_{k+1}$$

where

$$\beta_{k+1} = (k+1)\,\sigma n\,\Delta x$$

is the probability that if there are $k+1$ particles, one hits a target and is removed; whereas

$$1 - \beta_k = 1 - k\,\sigma n\,\Delta x$$

is the probability that with k particles all miss.

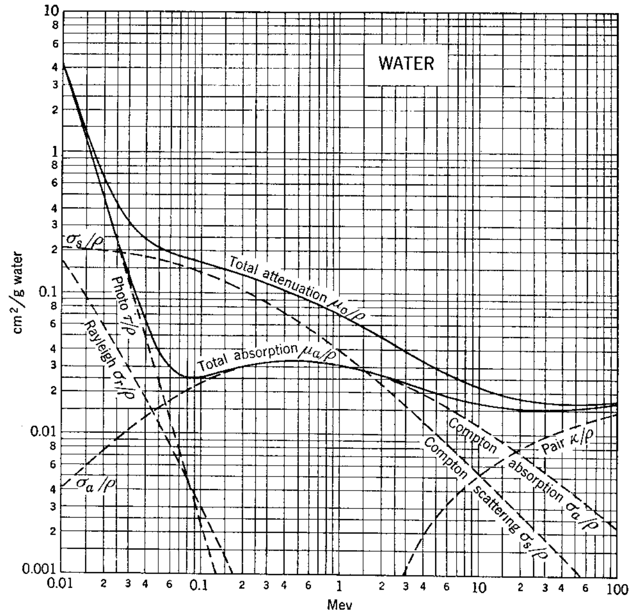


Fig. 1.3 Mass attenuation coefficients for photons in water. The individual curves have the same significance as in Fig. 1.2 and were computed from the tables of atomic cross sections prepared by G. R. White (W38).

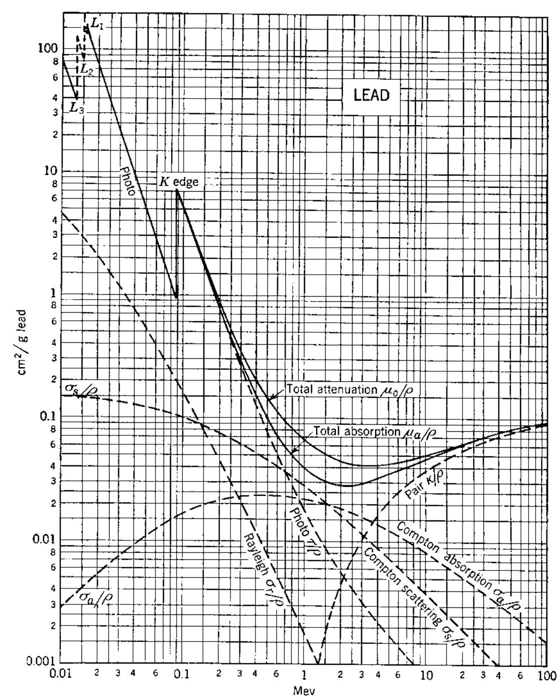


Fig. 1.5 Mass attenuation coefficients for photons in lead. The individual curves have the same significance as in Fig. 1.2 and were computed from the tables of atomic cross sections prepared by G. R. White (W38). The corresponding linear coefficients for lead may be obtained using ρ = 11.35 g/cm³ Pb.

This leads to a differential equation for probabilities (Kolmogorov forward difference equation) that can be solved by various mathematical tricks. The equation is

$$\frac{dp_k}{dx} = \sigma n \left[(k+1)\, p_{k+1} - k\, p_k \right] ;$$

however there is no need to solve for the probabilities since all we need is the average, or expected number

$$K(x) = \sum_{k=0}^{\infty} k\, p_k(x) .$$

It is not hard to see that the expected number satisfies a differential equation

$$\frac{dK(x)}{dx} = -\sigma n\, K(x)$$

whose solution is the exponential relation

$$K(x) = K(0)\, e^{-\sigma n x} .$$

If we consider K the number of particles that arrive in a unit area in a time dt we can convert this to the usual relation for the falloff in intensity, of a beam of particles passing through matter:

$$I(x) = I_0\, e^{-\sigma n x} .$$

The distance in which the intensity falls by a factor $e^{-1} = 0.3678 \ldots$ is

$$\lambda \overset{df}{=} \frac{1}{\sigma n} ,$$

and is called the *radiation length* or sometimes the *mean free path*.

The effective area σ is called the total cross section of the target atom for all possible reactions involving the specific beam particle. It is, as we have seen, a measure of reaction probability and must be calculated in general using quantum mechanical techniques.

5. Radiation exposure and dosage units

By the 1930's some standards for radiation safety had been adopted, based on a unit of exposure called the *roentgen*: one roentgen is that amount of radiation that produces, in one cm^3 of dry air at 0^o C and standard atmospheric pressure, ionization of one electrostatic unit of charge (the electron charge is 4.8×10^{-10} esu). This was a useful definition as long as electroscopes or ion chambers were the key technique for measuring radiation. The roentgen is still in use as a measure of exposure to X rays or γ rays[12].

More recently a unit of absorbed dose has been adopted, based on the energy per unit mass deposited by ionizing radiation. The MKS (or SI) unit is the *gray* (Gy): one gray is an absorbed dose of one joule per kilogram. Since a gray is a very large dose, it is conventional (and convenient) to work with the cgs unit, the *rad*, a dose of 0.01 gray. That is,

$$1 \text{ gray} = 100 \text{ rad},$$

and one rad is the deposition of 100 ergs per gram of target material. (Work it out.)

There is yet another dosage unit in common use today, based on biological equivalence. As we shall see when we discuss other forms of ionizing radiation, some forms are more effective in depositing energy in living organisms than others. The reference form of radiation is 200 KeV X rays (or γ rays—same thing). One grey of 200 KeV X rays produces a unit dose of one *sievert* (Sv).

Since α particles[13] are about 15 times as effective in depositing energy as 200 KeV X rays, 1.0 Gy of

12. Photons with energies up to 100 KeV are called X rays; above this energy they are called γ rays.
13. As Rutherford showed, the α particle is the nucleus of ^{4}He, emitted in radioactive decay.

α particles produces a dose of 15 Sv. The *rem*, or "radiation equivalent, mammal" is 0.01 Sv, and was originally defined to be the dose that would be the equivalent of one roentgen of exposure. In other words,

$$1.0 \text{ Sv} = 100 \text{ rem.}$$

The amount of damage done by ionizing radiation is determined by how much energy it deposits per kilogram of living tissue, because that tells us approximately how many chemical reactions it can cause (of which some small fraction will be dangerous to the living cell). We measure dosage in *rad*s. This is equivalent in most cases to the more common unit, the *REM* (*R*adiation *E*quivalent *M*ammal): a measure of energy delivered per kilogram of tissue. Most doses, say from natural backgound radioactivity, are much smaller than 1.0 REM, so we measure for convenience in 1/1000 of a REM, or *milliREM*. Thus, 1 milliREM = 10^{-5} J/Kg.

For comparison, a whole-body radiation dose that kills 50% of those exposed[14] is about 400 REM, or about 200-300 Joules of energy. A 0.22 caliber bullet delivers about 135 J, and also kills about 50% of those hit in vital areas of the body.

The environment to which we are continually exposed is radioactive. We receive the following doses of radiation annually, on average:

Source	Annual dose (mR)
Solar and cosmic rays	50
Terrestrial soil, air (U, Rn,Ra, Th)	55
Internal (^{40}K)	20
Manmade (X-ray)	
Dental	20
Chest	150
Other organs	200
Total	500

There are substantial variations in the doses people receive, based on location and occupation. For example, in Texas the natural background is about 100 mR/yr but in Colorado and Wyoming it is 250 mR/yr. In some places in Brazil and southern India the numbers can get as high as 2000 mR/yr.

Living in a stone or brick house rather than a wooden one increases the average dose by 40 mR/yr.

Airline crews flying above 35,000 feet receive about six times more radiation from space, *i.e.* about 300 mR/yr in addition to their other exposures.

6. Effects of radiation exposure

The amount of damage done by ionizing radiation is determined by how much energy it deposits per kilogram of living tissue, because that tells us approximately how many chemical reactions it can cause (of which some small fraction will be dangerous to the living cell).

How is the effect of ionizing radiation on human beings determined? And how does the EPA, for example, set standards for radiation exposure? At very low doses, ionizing radiation produces no effect on human beings or other living organisms that can be deteced with present biomedical technology. Everything we can say about radiation effects on living organisms is based either on extrapolation (downward) from known effects of large doses. To help you understand what "small" and "large" mean, the average background radiation dose (from the environment being naturally radioactive) is about 170 mR/year to each person in the United States. On the other hand, large doses ranging form hundreds to thousands of rem have been received by the atom-bomb survivors of Hiroshima and Nagasaki, by workers in nuclear

14. That is, they die of acute radiation sickness.

facilities (reactors and weapons plants), by victims of radioactive fallout from test explosions in the atmosphere, by (underground) uranium miners[15], and by patients being treated for disease[16]. The sample sizes are shown below:

Category	Sample size	Est. Dose (REM)
A-bomb survivors	23,979	≥ 130
U miners	4,146	468†

†Dose received over 20 years

In addition to the data (based on dose estimates rather than actual measurements) on human beings, various living organisms have been exposed to radiation in the laboratory.

When a living cell is bombarded by penetrating radiation, several things can happen:

1. it can be killed immediately;
2. it can be rendered incapable of division so that its life is greatly reduced (and it is not replaced);
3. its genetic material can be so altered as to either give rise to a mutation or, more commonly, to a cell lacking some essential control mechanism—that is a cancer cell.

Precisely how much energy, and in what precise form, must be applied to a cell to bring about any of these outcomes is not known with any precision. However, experiments on cells *in vitro* (using X rays) indicate that several photons must hit a cell before it cannot survive. The figure below indicates how this can be inferred from the data. Let us loosely define a "hit" as some amount of energy depositied in the cell.

Manifestly, the average number $\bar{n}$ of hits per cell will be proportional to the dose. If the fraction of cells that survive is plotted against the dose, we obtain curves resembling the solid line (highest curve) in the figure. Note that the vertical scale is the logarithm of the fraction surviving, whereas the horizontal scale is the dose.

Suppose only one hit killed a cell. The fraction surviving in that case would represent the cells that received no hits at all. According to Poisson statistics,

$$p_0 = e^{-\bar{n}}$$

so that the plot of the logarithm of the fraction surviving against dose would then be a straight line of negative slope, such as the dashed curve in the figure.

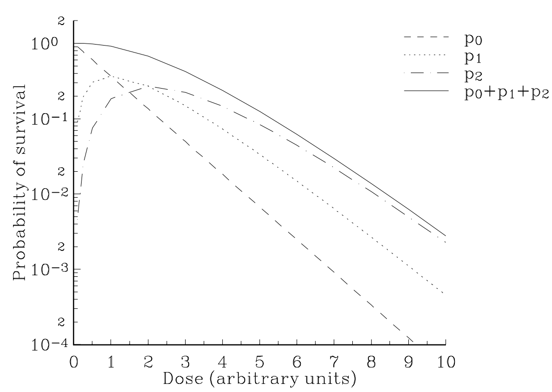
Also plotted are the fractions of the cells that receive 1 and 2 hits—given by

$$p_1 = \bar{n}\, e^{-\bar{n}}$$

and

$$p_2 = \frac{\bar{n}^2}{2}\, e^{-\bar{n}} .$$

Survival of irradiated cells *vs.* dose



The solid curve is the fraction receiving two or fewer hits, *i.e.* the sum of p_0, p_1 and p_2. The

15. The latter are exposed to radon, whereas open-pit uranium miners are not.
16. Primarily cancer, although other diseases havebeen treated by irradiation.

actual data look much more like the solid curve than the dashed one, meaning that cells must be hit multiple times to be inactivated.

The implications of this simple kind of experiment is that cells possess a repair mechanism that can cope with small amounts of irradiation, but which can be overwhelmed by large doses. Given that life on Earth is constantly bathed in background radiation, the fact that cells have evolved defensive tactics should not be too surprising.

Injury and death of a complex organism (a human being, *e.g.*) from large radiation doses are relatively easy to detect and understand. The most sensitive organs and tissues are those in which the cells divide most rapidly. The reason for this is that the most sensitive part of a living cell, the DNA (which acts like a data tape that is interpreted by cellular machinery to control the processes of life—not to speak of reproduction) gets wound up into a compact form immediately prior to cell division. At this stage it is more vulnerable to radiation damage. *Ipso facto*, cells that divide rapidly (for example the lining of the small intestine) will have a larger fraction of their collective DNA in this peculiarly vulnerable state at any given instant, hence are more likely to injured by radiation.

On the other hand, cells that divide especially slowly, such as the neurons of the central nervous system, are less susceptible to radiation exposure.

Thus the chief cause of death in people exposed to whole-body doses of ≥ 400 REM is damage to the gastrointestinal system. The intestines become ulcerated, can bleed or become gangrenous, lose their ability to absorb nutrients, and unless enough survive to replace the damaged cells, the victim dies, in effect, by starvation.

Larger doses kill more quickly and certainly by internal hemorrhage and blood loss. The table below describes the chief forms of acute radiation sickness, brought on by large doses over a short period.

The detection of mutagenesis and cancer induction in living organisms is much more subtle. This requires exposing a large population to sublethal doses, followed by a careful search for effects. The problem is that most complex organisms possess defense mechanisms that can recognize and kill most transformed cells. Thus it can be difficult to induce tumors in laboratory mice (whose defenses have been weakened by generations of inbreeding) and virtually impossible to do so in wild strains.

Forms of Radiation Sickness

Time	Cerebral & cardio-vascular	Gastro-intestinal	Hemo-poietic
	≥ 20,000 rem	2,000 rem	400 rem
1st day	nausea vomiting diarrhea headache erythema disorientation agitation ataxia weakness somnolence coma convulsions shock death	nausea vomiting diarrhea	nausea vomiting diarrhea
7-14 days		nausea vomiting diarrhea fever erythema emaciation prostration death	
14-28 days			weakness fatigue anorexia nausea vomiting diarrhea fever hemorrhage epilation recovery (?)

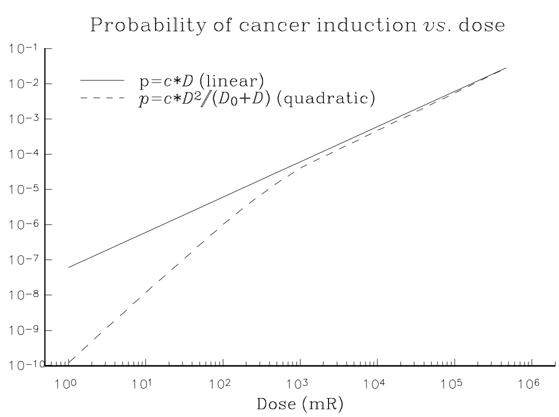
Thus, when we speak of the effects of very small radiation doses that do not cause any detectable injury to the human body, we must extrapolate downward from doses large enough to produce an observable effect.

Thus, for example, the exposure of the uranium miners to an average dose of 23.4 REM annually, and the 119 excess (lung) cancer deaths seen in this sample extrapolates to a probability of cancer induction of

$$\frac{119}{4146 \times 4.68 \times 10^5} \approx 10^{-7}/\mathrm{mR}\ .$$

This method of downward extrapolation is called the "linear hypothesis" because it takes no account of the time factor (that is, the rate at which people are exposed). Its essential assumption is that radiation damage is radiation damage, so that all one needs to know is the total dose received. To some extent this hypothesis is justified by the observation of cancer induction among the irradiated survivors of Hiroshima and Nagasaki bombings with comparable probability, despite the fact that their exposure was short- rather than long-term.

On the other hand, all data seem to imply a threshold, below which radiation exposure is much less



likely to induce cancer. That is, suppose the probability of induction varies quadratically with dose for doses below 500 mR. Then we would expect to see something resembling the lower curve in the figure below, rather than the upper curve (which reflects the linear hypothesis.

Epidemiologists studying this question have compared areas of the world with different background radiation exposures, in an effort to elucidate this matter. For example they have estimated that on the linear hypothesis 10% of observed cases of leukemia would be radiation induced. If one assumed a quadratic relation of response to dose, this would be reduced to less than 1%. Thus, with regional variations of background dose of more than 2, one would expect to be able to distinguish between—say—Louisiana with an average of 100 mR/yr, and Colorado, with 300 mR/yr. But Colorado has less leukemia than Louisiana!

7. Appendix

Units of Radiation and Exposure

Unit	Type/Definition
curie (C)	**Source strength:** 3.7×10^{10} disintegrations/sec
roentgen (R)	**dose:** produces 1 esu of ions in 1 cm^3 dry air
gray (Gy)	**dose:** deposits 1 Joule in 1 Kg
rad	**dose:** 0.01 gray; 1 Gy = 100 rad
sievert (Sv)	**dose:** 1 gray of 200 KeV γ rays
rem	**dose:** 0.01 Sv; 1 Sv = 100 rem