George Mason University Department of Physics

Introduction to Radiation Safety and Radiation Dosimetry

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1 Introduction

The use of radioactive materials is regulated by Federal and State laws. To maintain compliance with these laws, it is important that instructors and students in laboratory courses in which radioactive sources are used be familiar with safety regulations, as well as with their scientific basis.

This document has two purposes:

- To describe the physical processes by which nuclear radiation interacts with matter, and present the basic ideas of radiation dosimetry.
- To summarize the relevant safety regulations regarding the use and storage of radioactive sources in the Department of Physics.

Some knowledge of physics is assumed in the descriptions below.

2 Basic Dosimetry

Many empirical studies have established a relationship between biological damage and the energy deposited, by elementary particles and nuclei, in a biological system. [1] While there is a wide range of specific responses to different types and intensities of radiation, the specification of biological damage usually starts with a physical quantity called the *dose*. The dose, D is defined as the absorbed energy per unit mass of absorber, i.e.

$$D = \frac{\Delta E}{\Delta m} \tag{1}$$

in which ΔE is the absorbed energy in a mass Δm. The dose is actually an intensive quantity. The SI unit of D is the *Gray* (Gy) which is 1 joule/kilogram. An older and more commonly known unit is the *rad*, which is 6.24×10^{10} MeV/kg. In Table 1, below, several dosimetric quantities are given in different units.

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[1] In addition to α, β, and γ particles, which are, respectively, a helium nucleus, an electron or positron, and a photon, energetic protons, neutrons and other heavier nuclei may also cause radiation damage.

Actual biological damage is usually correlated with another quantity, the *biological dose* or the *dose equivalent*, D_B, which corrects the dose for specific types of energy-losing particles.

$$D_B = QD$$

in which Q is a correction factor, sometimes called a "quality factor", which depends on the particle and sometimes its energy. For example, for a γ ray, $Q = 1$; for an α-particle, $Q = 20$. Even though the dimensions of D_B are the same as those of D, there are different units. The SI unit of biological dose is the *Sievert*, which is 1 Gray $\times Q$. The older unit is the *rem*. It is evident that it is possible to have different doses to different parts of a biological system.

A particular radioactive source is characterized by the type of particle emitted, and the rate and energy spectrum of each type. The rate at which nuclei are transformed is called the *activity*. Its SI unit is the *Becquerel* (1 Bq = 1 decay/sec.) The older unit is the *Curie* (1 Curie = $3.7 \times 10^{10} sec^{-1}$.) Because activity is defined in this way, a multi-step decay with the emission of several particles from different intermediate states is regarded as a single transformation of the original nucleus.

Table I

Quantity	SI Unit	SI Equiv	Old Unit
Dose	1 Gray	1 J/kg (= 6.25×10^{12}MeV/kg)	100 rad
Dose Equivalent	1 Sievert	1 J/kg	100 rem
Activity	1 Becquerel	1/sec	$1/(3.7 \times 10^{10})$ Curie

2.1 Range of Doses

Some perspective may be obtained from the numerical values of two specific doses[1]:

- **Natural Background Dose**. This is due to natural radioactivity, and to cosmic ray particles. It ranges from 0.4 to 4 mSv (40 - 400 mrem) per year. The average USA value is 0.8 mSv (80 mrem.) This dose is delivered to the entire human body.

- **Lethal Dose** The whole body dose which results in 50% mortality in 30 days (assuming no treatment) is 2.5 - 3.0 Sv (250-300 rem).

2.2 USA Maximum Permitted Dose Limits

The U.S. Nuclear Regulatory Commission sets official limits on the dose which radiation workers may receive.

- The maximum annual whole-body dose which radiation workers may receive is 50 mSv (5000 mrem.) Persons exposed to the maximum permissible dose will not demonstrate any somatic effects during their lifetime.

- The maximum permissible whole-body dose for the general population is 1 mSv (100 mrem), above background, per year.

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3 Dose Calculations

A fundamental problem in dosimetry is to predict the dose/unit time produced by a specific source and absorber arrangement. This is the subject of many papers and books, since, in general, the dose rate will depend on the details of the source and absorber spatial distribution, and requires complicated calculations for accurate determination. However, there are a few simple models which may be used to make approximate predictions. To develop these, we must first study energy loss rates.

3.1 Ionization Energy Loss by Charged Particles

The energy of a particle emitted in radioactive decay is ultimately thermalized by electromagnetic interactions. The dominating process is *ionization* and *excitation* of atoms and molecules by energetic charged particles.[2] The electric field produced by a charged particle can deliver sufficient impact to nearby atoms or molecules to excite and/or ionize them. The effect is described by the quantity $(dE/dl)_{ion}$, which is the average energy loss by the charged particle, per unit length of absorber. The negative of this quantity is called the *stopping power.*

This quantity depends on the charge, mass and energy of the particle, and on Z and A of the absorber material. The energy dependence of $\frac{dE}{dl}_{ion}$ is illustrated in Figure 1. Note that this figure actually plots the quantity $(dE/dx)_{ion}$, where the quantity x is the "column density", $x = \rho l$, where ρ is the mass density of the absorber, and l the distance. The cgs unit of x is gm/cm^2; it is sometimes called "grammage". Thus the units given in the figure for $(dE/dx)_{ion}$ are $MeV/gm/cm^2$. This choice of unit takes out the strong dependence of $\frac{dE}{dl}_{ion}$ on the density of the absorber.

There are several noteworthy features of this figure:

1. $(dE/dx)_{ion}$ is proportional to z^2 of the energetic particle. So, for example, an α-particle loses energy 4 times more rapidly than a particle of the same mass and energy, but unit charge.

2. At low velocities,
$$\frac{dE}{dx}_{ion} \propto \frac{1}{v^2}$$
where v is the velocity of the particle. At low speeds, this breaks down; the particle becomes less effective at producing ionization. When the particle speed becomes comparable to that of atomic electrons, the particle starts to "grab" atomic electrons and intermittently becomes neutral.

3. $(dE/dx)_{ion}$ tends to "bottom out" once the particle becomes fairly relativistic. We call such particle "minimum ionizing". A general rule of thumb is
$$\frac{dE}{dx}_{min;ion} \approx 1.5 - 2\, MeV/gm/cm^2$$

4. For very relativistic particles, $(dE/dx)_{ion}$ increases over its minimum value. This is due to the Lorentz contraction of the particle's electric field.

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[2] Neutral particles lose energy by transfering energy to charged particles, eg., the photon loses energy by Compton scattering, pair production, and the photoelectric effect.

The first calculations of $(dE/dx)_{ion}$ were made by Bethe in 1930 [2]. Since then, many refinements have been included in the calculations. Figure 1 was obtained using formulae from calculations by Sternheimer [3].

A particle of energy E_i, incident on a thick enough absorber, will eventually stop, due to ionization energy loss. The distance, or column density travelled before stopping is called the *range* of the particle. This is formally related to $(dE/dx)_{ion}$ by

$$R(E_i) = \int_{E_i}^{0} \frac{dE}{\frac{dE}{dx}_{ion}}$$

A plot of $R(E)$ vs E for electrons in aluminum is given in Figure 2.[3]

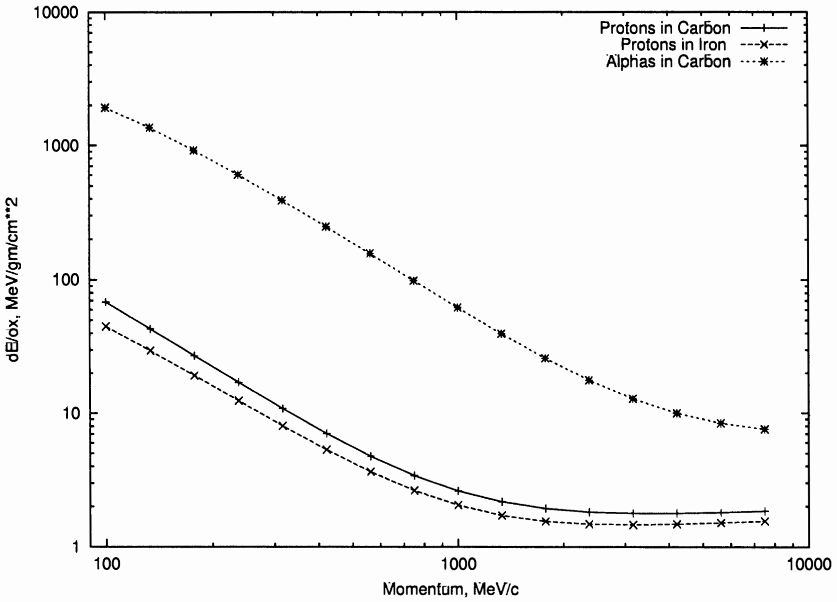

Figure 1: Ionization energy loss rates vs. particle momentum.

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[3] Data from Reference [4], page 100.

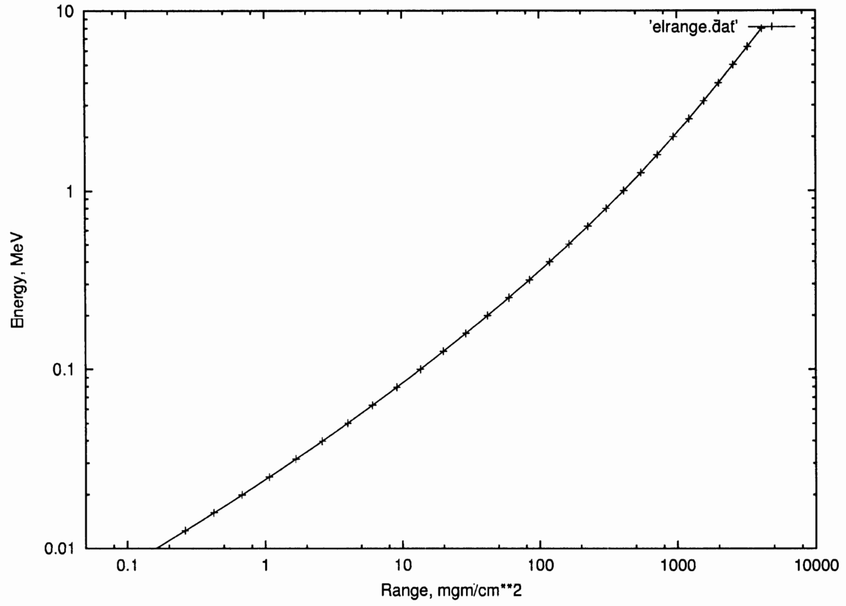

Figure 2: Energy vs. range for electrons in aluminum.

3.2 Dose for Charged Particles Incident on a Thin Slab

Suppose a known *flux* of charged particles is incident on an area ΔA of a thin slab of thickness Δl. The flux, ϕ, is the number of particles per unit area per unit time, i.e.

$$\phi = \frac{d^2n}{dAdt}$$

If the slab is thin, the energy lost in the slab, per particle, is

$$\Delta E = \frac{dE}{dx}_{ion} \rho \Delta l$$

The energy loss per unit time is then

$$\begin{aligned} \frac{\Delta E}{\Delta t} &= \phi \frac{dE}{dx}_{ion} \Delta A \rho \Delta l \\ &= \phi \frac{dE}{dx}_{ion} \Delta m \end{aligned}$$

where Δm is the mass of that part of the slab hit by the beam of particles. So the dose rate is just

$$\frac{dD}{dt} = \phi \frac{dE}{dx}_{ion} \tag{2}$$

This formula is also valid for gamma rays incident on a thin slab, provided the appropriate (dE/dx) is known.

3.2.1 Example

We calculate here the contribution of cosmic-ray muons to the annual "natural" dose in a thin slab of carbon. The flux of cosmic ray muons at sea level is approximately

$$\phi_\mu = 1.6 \times 10^2 m^{-2} sec^{-1}$$

The average muon energy is about 2 GeV/c and almost all the muons are minimum ionizing. A human body is mainly oxygen, carbon and hydrogen. A slab of carbon provides a good approximation to the energy absorption properties of a person.[4] For carbon,

$$\frac{dE}{dx}_{min;ion} = 0.178\, MeV/kg/m^2$$

So, using equation 2 , the dose rate is

$$\frac{dD}{dt} = \phi_\mu \frac{dE}{dx} = 4.56 \times 10^{-12} Gray/sec$$

Over an interval of 1 year (1 year = 3.15×10^7 sec) the total dose is

$$D = 1.43 \times 10^{-4} Gray = .0143 rad$$

For a muon $Q = 1$, so the annual biological dose is 143 μSv or 14 $mrem$. The dose due to cosmic ray muons is part of the "natural" background dose received by the general population. The average total "natural" background in the USA is about 800 μSv or 80 $mrem$.

3.3 Dose Calculations for Gamma Rays

The intensity of a photon beam falls exponentially with distance in an absorbing medium:

$$I = I_0 e^{-(\mu_{en}/\rho)x}$$

where I_0 is the incident intensity, x is the column density, ρl, and (μ_{en}/ρ) is the energy-corrected photon attenuation coefficient. It takes into account all the mechanisms which will result in energy deposition in the vicinity of the photon.[5] In general (μ_{en}/ρ) is a function of the photon energy , E_γ. A plot of (μ_{en}/ρ) for water vs. photon energy is shown in Figure 3.

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[4] There is a standard human body composition used for dosimetric calculations. It is given in Reference [4]

[5] A graph of (μ_{en}/ρ) vs E_γ for various elements is given in Reference [5]

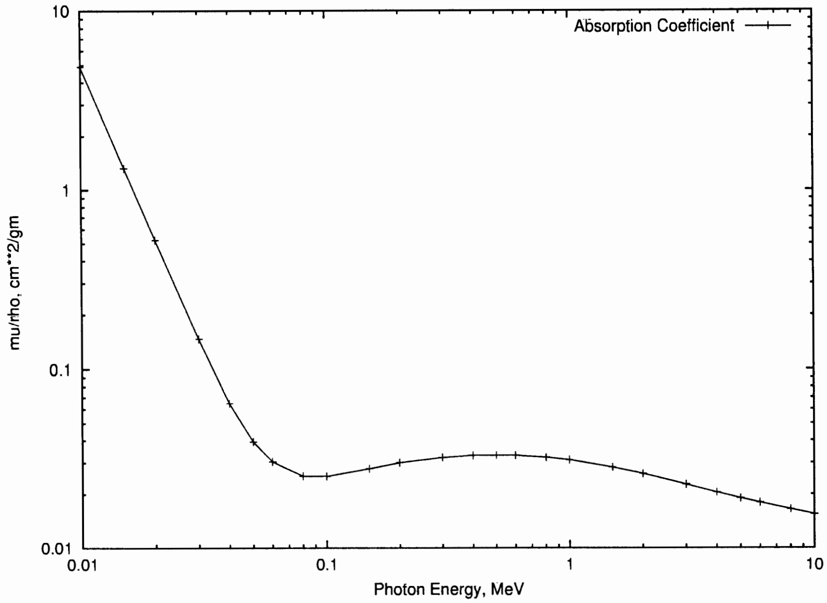

Figure 3: The photon energy absorption coefficient, for water, vs. photon energy.

To use the above equation for a dose calculation in a thin slab, we make a Taylor expansion of the exponential (assuming the slab is thin enough to make the argument of the exponential "small".)

$$I \approx I_0(1 - (\mu_{en}/\rho)\Delta x)$$

Or

$$\frac{\Delta I}{I} \approx (\mu_{en}/\rho)\Delta x$$

Now the intensity is the average energy per area-time, so the above equation may be written:

$$\frac{\Delta E_\gamma}{E_\gamma} = (\mu_{en}/\rho)\Delta x)$$

And so the energy loss rate is

$$\frac{dE}{dx} = E_\gamma(\mu_{en}/\rho) \tag{3}$$

This expression may be used, with equation 2, to compute a thin-slab dose.

3.3.1 Example

As an example, let us calculate the dose rate into a "thin" carbon absorber, of a 1-Curie gamma source, at a distance of 1 meter from the source. Assume the source produces monoenergetic gamma rays, of energy $E_\gamma = 1MeV$.. An approximate value for μ_{en}/ρ for carbon at $1MeV$ is

$$\mu_{en}/\rho = .003m^2/kg$$

The flux. ϕ, is obtained from the activity, A, assuming isotropy,

$$\phi = \frac{A}{4\pi r^2} = 2.9 \times 10^9 m^{-2} sec^{-1}$$

So the dose rate is

$$\begin{aligned}\frac{dD}{dt} &= \frac{\dot{A}}{4\pi r^2}\frac{dE}{dx} \\ &= 1.39 \times 10^{-6} Gy/sec\end{aligned}$$

Using $Q = 1$ for γ's gives

$$\frac{dD_B}{dt} = 1.39 \mu Sv/sec$$

It is customary to quote such dose rates as a dose per hour, so

$$\frac{dD_B}{dt} = 5.01 mSv/hr = 500 mrem/hr$$

Some readers may want to estimate the dose rate for a real source, such as ^{60}Co. In doing this, it is necessary to take account of the fact that this particular source produces a low energy beta, and two gammas, each of energy $\approx 1 MeV$, for each nuclear transformation.

3.4 Radiation by electrons

Because of their relatively small mass, electrons may lose significant amounts of energy by radiation (bremsstrahlung), as well as by ionization. The rate of energy loss by radiation can be shown [7] to be, at high energies,

$$\frac{dE}{dx}_{rad} = -\frac{E_\gamma}{X_{rad}}$$

where the quantity X_{rad}, the *radiation length*, is an energy-independent property of the absorbing medium. Table 2, below, gives radiation lengths for several materials. Because the ionization energy loss rate is approximately constant for relativistic electrons, at a high enough energy, radiation loss will be dominant. There is an energy in any given absorber at which the radiative and ionization loss rates are equal. This energy is called the "critical energy", E_c. Table 2 also displays these. When an electron's energy is much less than E_c, radiation losses may be neglected in dose calculations. This will be the case for few-MeV electrons.

Table 2

Material	Radiation Length gm/cm^2	Critical Energy MeV
Air, STP	36.7	66.7
Water	36.1	73.2
Carbon	42.7	76.0
Iron	13.8	20.48
Lead	6.37	7.20

4 Radiation Safety Regulations

The following regulations, extracted from the document submitted by the University to the US Nuclear Regulatory Commission for obtaining a license to use radioactive sources, are relevant to source use in the Advanced Laboratory:

1. All radioactive material will be stored in a lead container and locked in a designated cabinet when not in use.
2. A monitoring dosimeter or film badge will be worn by one person in each group handling radioactive material of strength greater than $20\mu curie$. The person closest to the source will normally wear this device and any reading recorded will be attributed in the log book to all persons in the group.
3. Under no circumstances will food be brought into the laboratories where radioactive sources are used.
4. The Approved User (your instructor) will ensure that both monitoring devices (i.e. survey meters) and recording devices, (i.e. dosimeters/film badges) are present and operational prior to removing radioactive sources from their storage container.
5. Pregnant women are advised not to work with radioactive materials. The NRC has recommended holding prenatal occupational exposure to 500 mrem or less during the entire gestation period.
6. All radioactive materials, containers used for storage of radioactive materials, work areas, and laboratory glassware shall be marked with a "Caution Radioactive Materials" sign.

The Advanced laboratory does not currently perform experiments with open or unsealed sources.

References

[1] R. Gatto et al., Review of Particle Properties, Physics Ltters **B170** 47, (1986)

[2] H. Bethe, Ann. Physik **5**, 325 (1930).

[3] R. M. Sternheimer, Phys. Rev. **103**, 511 (1956).

[4] "Introduction to Health Physics", by Herman Cember, Pergamon Press, 1989, Appendix III.

[5] Rev Mod Phys **56**, (1984).

[6] "Physical Aspects of Irradiation", NBS Handbook No 85, Washington DC, US Govt. Printing Office, 1964.

[7] H. A. Bethe and W. Heitler, Proc. Roy. Soc. London, **A146**, 83 (1934).