PART III

Interaction of Radiation with Matter

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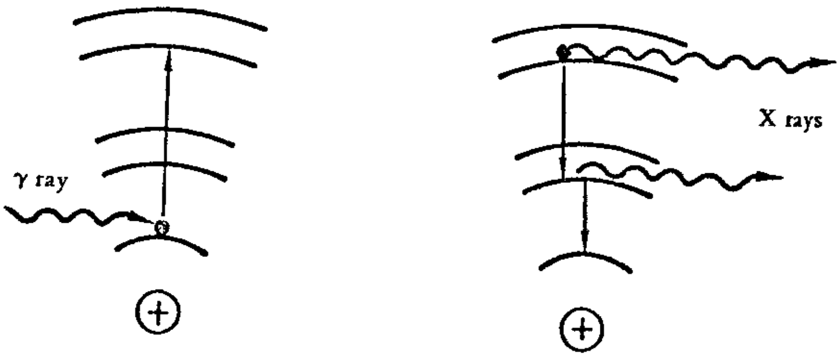
SECTION I

Mechanism of Interaction

A. Molecular Excitation

If the energy imparted by a radioactive particle is less than the energy required to ionize an orbital electron, excitation of electron(s) to higher energy levels of the molecule occurs. Deexcitation occurs by emission of low energy radiation in the form of x-rays, visible light, etc.



(a) (b)

Fig. 1. Excitation by gamma ray: (a) the gamma ray excites the electron to a higher energy level; (b) the electron falls back to the original level in two steps, with X rays or visible light emitted in each step.

B. Ionization

If the energy imparted by radioactive particles is equal to or greater than the energy required to remove an orbital electron, ionization results in formation of an ion pair.

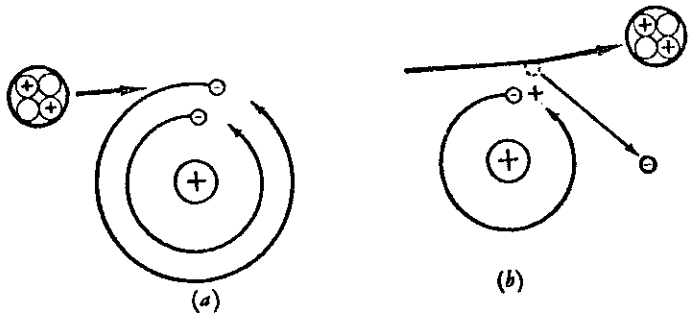


Fig. 2. Formation of an ion pair by α particle: (a) alpha particle approaches an orbital electron and (b) causes it to leave the atom, producing an ion pair.

SECTION II

Absorption of Radiation

A. Heavy Particles:

Lose energy by interaction with coulomb field of orbital electrons. α particles traverse straight paths and have definite ranges in matter.

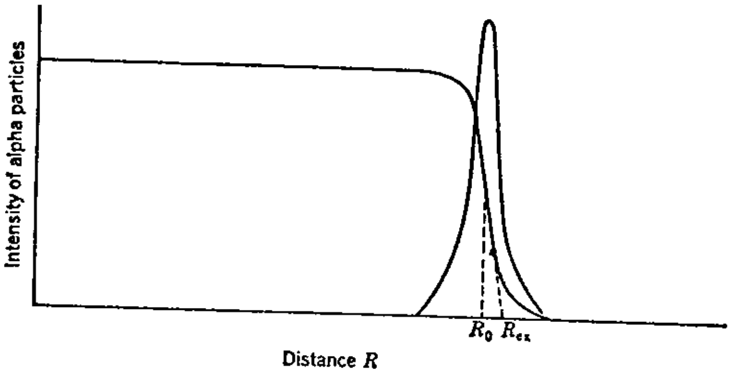


Fig. 3. Range curve for alpha particles.

Specific ionization - measures rate of energy loss

$-\frac{dE}{dX}$ per unit length in matter

$-\frac{dE}{dX} \alpha \frac{1}{v^2}$ v = velocity of α particle (1)

also,

$-\frac{dE}{dX} \alpha Z$ Z = atomic number of absorber (2)

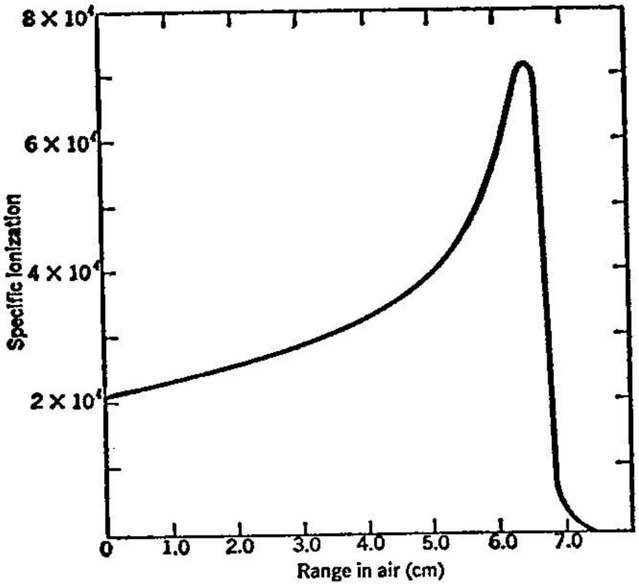


Fig. 4. Specific ionization of 7.7 MeV alpha particles in air. Important: ∿34 eV lost per ion pair formed in gases; ∿ 5 eV in solids and liquids.

TABLE I

W - AVERAGE ENERGY LOSS PER ION PAIR

Gas	Particle	w(ev)	Gas	Particle	w(ev)
Air	Electron	32.0	Helium	Alpha	42.7
Air	Proton	36.0	Neon	Alpha	36.8
Air	Alpha	35.5	Argon	Alpha	26.4
Hydrogen	Alpha	36.3	Methane	Alpha	29.4

B. Electrons:

Lose energy like α particles but for the same energy the velocity of electrons is much greater so lower specific ionization (remember $-\frac{dE}{dX} \propto \frac{1}{v^2}$).

Due to small mass, electron can lose large fraction of its energy in one collision. Large angle deflections result. Observed absorption follows exponential decrease with absorber thickness.

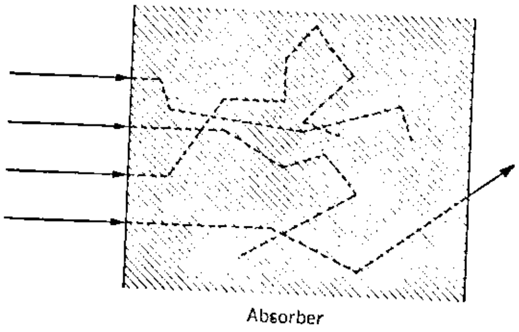
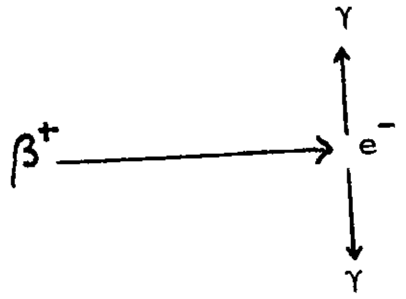


Fig. 5. Electron paths in an absorber

Bremsstrahlung - low energy X rays emitted when electrons are decelerated and bent in their paths by coulomb field of atomic nuclei.

Positron - interacts with electron, both annihilated and 2 gamma rays of 0.51 MeV each created.



C. Gamma and X rays:

Mechanism of interaction completely different than that of charged particle (α or electron); do not have a definite range in matter, exponential absorption.

1. Photoelectric Effect

Absorption of low energy γ rays by an atoms as a whole resulting in ionization

$$E_{e^-} = E_\gamma - E_{B.E.} \tag{3}$$

Where E_{e^-} = energy of photoelectron,
E_γ = energy of gamma ray absorbed,
$E_{B.E.}$ = binding energy of ejected elect

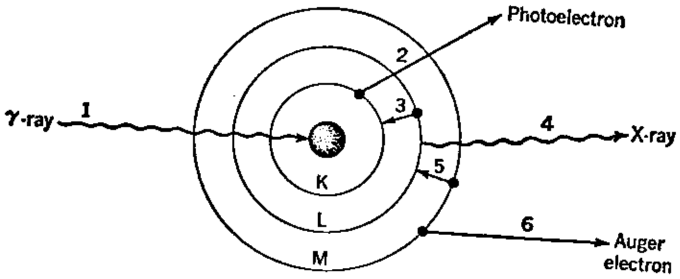


Fig. 6. The photoelectric effect: (1) complete absorption of the gamma ray by the absorber atom causing a photoelectron (2) to be ejected from the K-shell. The vacancy in an inner orbital results in electrons from higher levels falling down to fill all the lower vacancies, (3) and (5), x rays (4) characteristic of the absorber atom will be emitted with energies equal to the difference in binding energies of the two electronic levels involved in the transition. In place of an X ray, a low energy electron, known as an Auger electron(6) may be emitted.

2. Compton Effect

If the energy of the gamma ray is sufficiently large, rather than interaction with the atom as a whole, the γ ray may interact with any one of the orbital electrons as though it were essentially a free electron. Result: a Compton electron is ejected creating an ion pair.

$$E_{\gamma_2} = E_{\gamma_1} - E_{B.E._{e^-}} - E_{e^-} \tag{4}$$

If ejected e^- is from an inner orbital, X ray and Auger electron emission will occur as described for the photoelectric effect

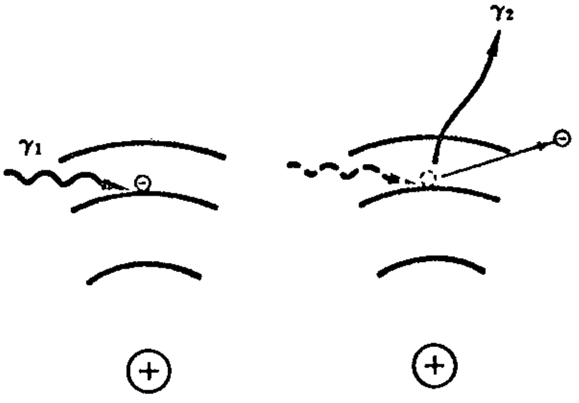


Fig. 7. Compton Scattering

3. Pair Production

Absorption of high energy γ rays cause formation of e^+

e^- pair. Threshold gamma energy is 1.02 MeV.

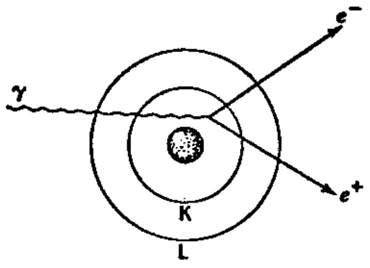


Fig. 8. Pair Production

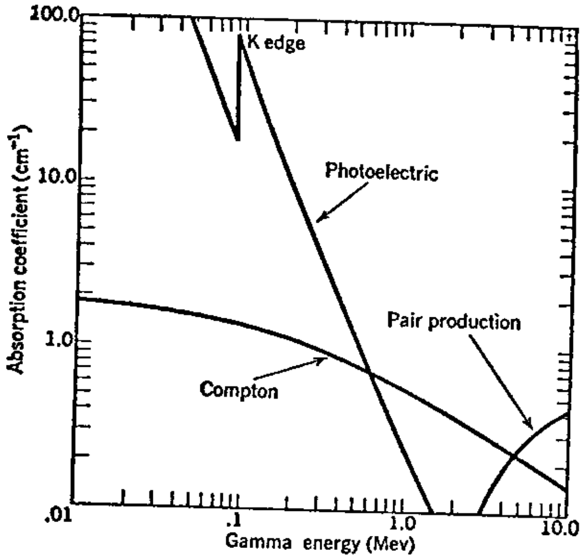


Fig. 9. Dependence on energy of absorption coefficients for lead.

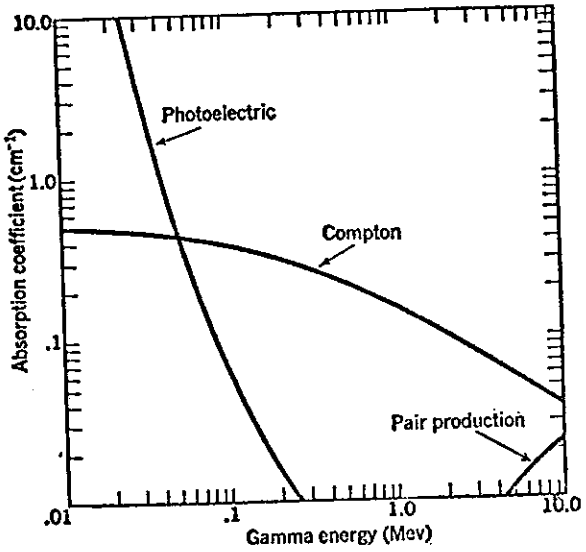


Fig. 10. Dependence on energy of absorption coefficients for aluminum.

SECTION III

Absorption Ranges in Materials

Range-distance of penetration in matter

A. Alpha Particle

Range in air = $R = 0.309\ E^{3/2}$ (MeV) (5)

Range in other absorbers: approximate

$$R = 0.173\ E^{3/2}A^{1/3} \qquad (6)$$

$E = E_{\alpha}$

A = atomic weight of absorber

R = thickness x density = cm x mg/cm^3

= range in mg/cm^2

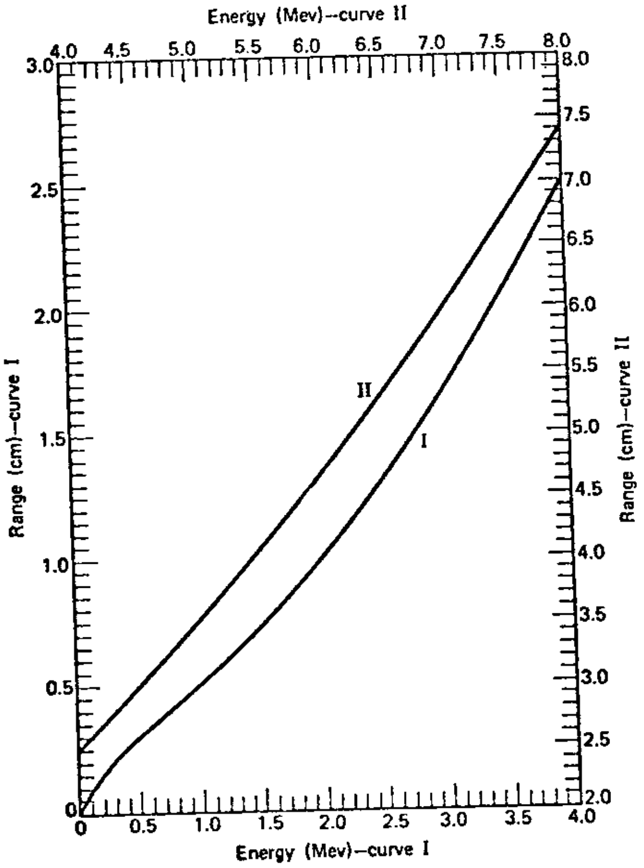


FIG. 11. Range-energy relation for alpha particles in air (15°C, 760 torr)

B. Beta Particles

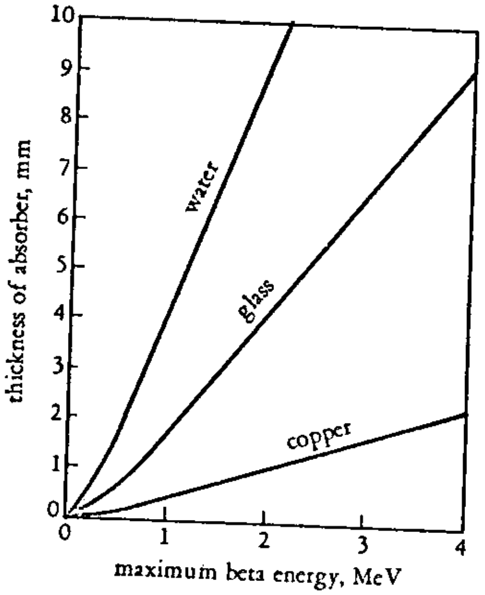


Fig. 12. Plot of absorber thicknesses required to stop beta rays completely.

C. Gamma Rays

Must consider contributions from photoelectric effect, Compton effect, and pair production.

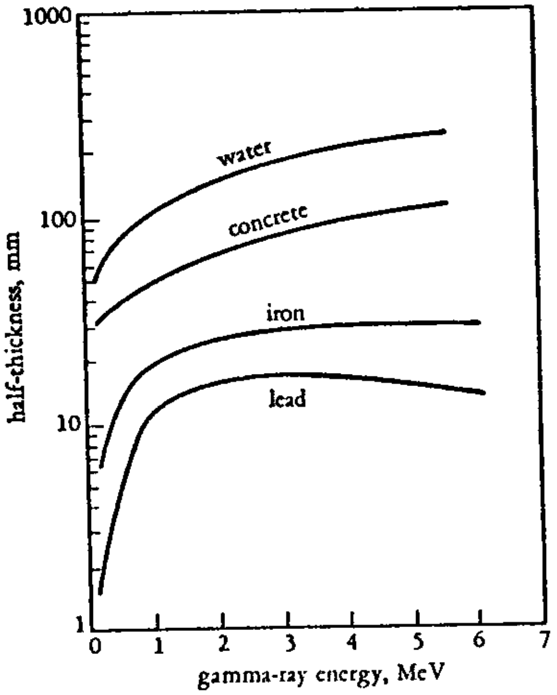


Fig. 13. Plot of absorber thicknesses required to reduce gamma ray intensity to one-half the original intensity.

SECTION IV

Radiological Safety

External Exposure - radiation source external to body

1. Alpha emitters - little or no danger, stopped by outer layer of dead skin tissue (can produce surface burn).

2. Beta emitters - can cause skin burns and biological damage.

3. Gamma and x-ray emitters - very penetrating, can damage internal organs.

Internal Exposure - introduction of radionuclide into body by ingestion, inhalation, etc.

1. Alpha emitters - bone seekers; high specific ionization can cause much radiation damage in a small volume.

2. Beta emitters - lower specific ionization, to evaluat danger you must consider particular biochemistry of the emitting element.

3. Gamma and x-ray emitters - cause damage over relatively large volume, comparable to external exposure.

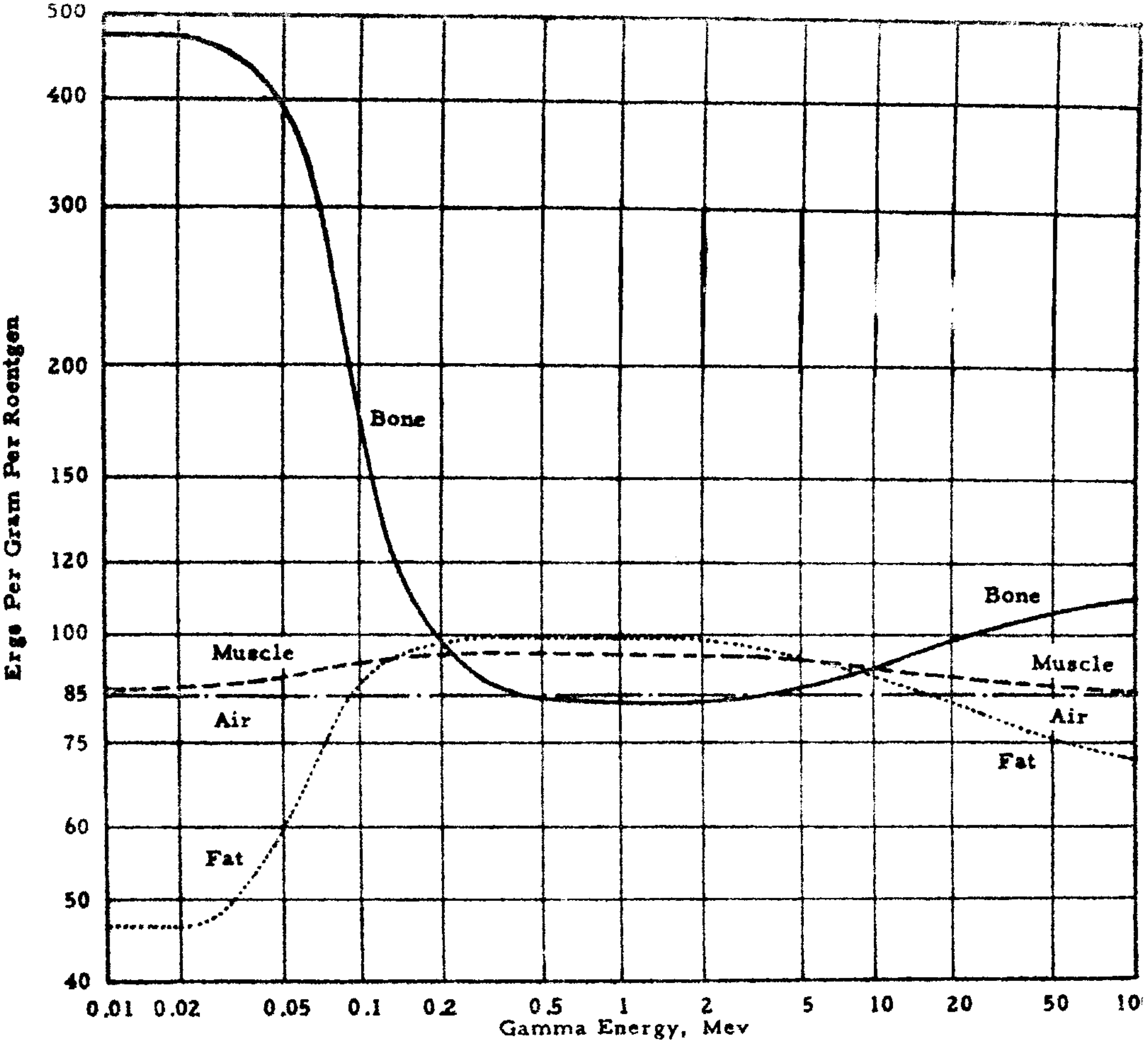


Fig. 14. Energy Absorption of gamma radiation in various tissues.

A. Units of Radiation

Since radiation produces ionization in its passage through matter, thereby losing energy, the extent of the ionization is used as a measure of the radiation field.

Roentgen $\equiv$ quantity of γ or X-ray radiation which produces 1.16×10^{12} ion pairs in 1 gm of air. Expresses intensity of radiation field, and not absorbed dose, limited to γ or X-ray radiation.

$$1.16 \times 10^{12} \ \frac{\text{ion pairs}}{\text{gm air}} = \text{absorption} \ \frac{87 \text{ ergs}}{\text{gm air}}$$

Rad $\equiv$ dose of any nuclear radiation which results in the absorption of 100 erg/gm (any material) Expresses absorbed dose, not limited to any particular type of radiation.

RBE (relative biological effectiveness) - ratio of absorbed dose of rads of γ radiation to absorbed dose of the given radiation required to give the same biological effect.

TABLE II

Radiation	RBE
x- or γ ray	1
β ray	1
Alphas	10
Slow Neutrons	5
Fast neutrons and protons (up to 10 MeV)	10

rem (roetgen equivalent man) - amount of radiation which produces the same biological effect as one rad of γ rays.

$$\text{dose (in rems)} = \text{RBE} \times \text{dose (in rads)} \qquad (7)$$

B. Effect of radiation exposure

TABLE III

	Effect of radiation doses on different organisms. LD-50/30 refers to a dose which has been found lethal for 50% of the organisms within 30 days. For micro-organisms about 10 times higher doses are required for killing than for inactivation.		
Micro-Organisms	Enzymes inactive at	$>2 \cdot 10^6$ rad	
	Virus (dry) inactivated at	30 000-500 000 rad	
	Bacteria inactivated at	2 000-100 000 rad	
	Human cells inactivated at	≥ 100 rad	
Plants	Flowers survive at	1 000 rad/d	during the growing season (normally the spring)
	Trees do not survive at	100 rad/d	
	Trees normally survive at	2 rad/d	
Animals	LD 50/30 for amoeba	100 000 rad	
	LD 50/30 for shells	20 000 rad	
	LD 50/30 for hamster	900 rad	
	LD 50/30 for rat	600 rad	
	LD 50/30 for humans	∿400 rad	
	LD 50/30 for goat	350 rad	

C. Typical Values of Some Radiation Doses

TABLE IV

Sterilization of surgical supplies	2×10^9 mrem
Lethal dose (whole body)	5×10^5 mrem
Cancer Therapy (to one region)	5×10^5 mrem
Whole body diagnostic x-ray	2×10^4 mrem
Dental x-ray (complete)	5×10^3 mrem
AEC limit for workers	5×10^3 mrem/yr
Natural background in Denver	130 mrem/yr
Natural background in Dallas	30 mrem/yr
Chest x-ray	100 mrem
^{40}K in body	16 mrem/yr
Living in a brick home	35 mrem/yr
Living in a wooden house	11 mrem/yr
Radium dial watch (wrist)	10 mrem/yr
Fallout from atomic tests	5 mrem/yr
Cross country jet flight (cosmic rays)	1 mrem/yr

D. Maximum Permissible Exposure Level for Man

1. 5 rems/yr or accumulate

2. exposure of 5(N-18) rems
   where N=age of individual
   For any 3 month period, maximum = 3 rems

TABLE V

Maximum permissible amount of radioactivity in body (MPB) and concentration in air and water (MPC) for 24 h/day. τ_{eff} is the effective half-life of the radionuclide in the body. All values refer to the critical organ, i.e. the organ which has the highest tendency of accumulating the radioisotope. (According to Report of Committee II on Permissible Dose for Internal Radiation, Pergamon Press, 1960).

Nuclide	Critical Organ	τ_{eff} days	MPB μCi	MPC, μCi/cm^3 water	air
^{3}H	Whole body	12	$2\cdot10^{3}$	0.05	$3\cdot10^{-6}$
^{14}C	Fat	12	300	$8\cdot10^{-3}$	10^{-6}
^{24}Na	Whole body	0.6	7	$4\cdot10^{-3}$	$6\cdot10^{-7}$
^{32}P	Bone	14.0	6	$2\cdot10^{-4}$	$2\cdot10^{-8}$
^{35}S	Testicles	76.4	90	$6\cdot10^{-4}$	$9\cdot10^{-8}$

Table V (cont.)

Nuclide	Critical Organ	τ_{eff} days	MPB μCi	MPC, μCi/cm^3 water	air
^{42}K	Whole body	0.52	10	$8 \cdot 10^{-3}$	10^{-6}
^{51}Cr	Whole body	26.6	800	0.2	$4 \cdot 10^{-6}$
^{55}Fe	Spleen	388	10^{3}	$8 \cdot 10^{-3}$	$3 \cdot 10^{-7}$
^{59}Fe	Spleen	41.9	20	10^{-3}	$5 \cdot 10^{-8}$
^{60}Co	Whole body	9.5	10	10^{-3}	10^{-7}
^{64}Cu	Spleen	0.42	10	0.03	$2 \cdot 10^{-6}$
^{65}Zn	Whole body	194	60	10^{-3}	$4 \cdot 10^{-8}$
^{90}Sr	Bone	$6.4 \cdot 10^{3}$	2	10^{-6}	10^{-10}
^{95}Zr	Whole body	55.5	20	1	$4 \cdot 10^{-8}$
^{106}Ru	Kidneys	2.48	3	$4 \cdot 10^{-3}$	$5 \cdot 10^{-8}$
^{131}I	Thyroid gland	7.6	0.7	$2 \cdot 10^{-5}$	$3 \cdot 10^{-9}$
^{135}Xe	Whole body				10^{-6}
^{137}Cs	Whole body	70	30	$2 \cdot 10^{-4}$	$2 \cdot 10^{-8}$
^{140}Ba	Bone	10.7	4	$2 \cdot 10^{-3}$	$4 \cdot 10^{-8}$
^{144}Ce	Bone	243	5	0.08	$3 \cdot 10^{-9}$
^{198}Au	Kidneys	2.7	20	0.02	$9 \cdot 10^{-7}$
^{210}Po	Spleen	42	0.03	$7 \cdot 10^{-6}$	$2 \cdot 10^{-10}$
^{226}Ra	Bone	$1.6 \cdot 10^{4}$	0.01	10^{-7}	10^{-11}
^{232}Th	Bone	$7.3 \cdot 10^{4}$	0.04	$2 \cdot 10^{-5}$	$7 \cdot 10^{-13}$
^{238}U	Kidneys	15	$5 \cdot 10^{-3}$	$6 \cdot 10^{-4}$	$3 \cdot 10^{-11}$
^{233}U	Bone	300	0.05	$4 \cdot 10^{-3}$	$2 \cdot 10^{-10}$
^{239}Pu	Bone	$7.2 \cdot 10^{-4}$	0.04	$5 \cdot 10^{-5}$	$6 \cdot 10^{-13}$

E. Recommended working conditions

1. Care must be exercised to avoid contamination and ingestion or inhalation of radioactive material.

2. Laboratory Safety Rules:

    a. No

        1. Mouth pipetting
        2. Smoking
        3. Eating or drinking

    b. Wear gloves

    c. Lab benches should be covered with absorbant paper

    d. When working with solids or liquids which might be inhaled use well ventilated hood or glove box

    e. Exposure to personnel must be minimized by use of shielding and distance. Use of tongs and tweezers recommended in handling radioactive samples.

f. Radioactivity must be stored in properly labeled containers under lock when not in use

g. Monitor hands and working area frequently with both alpha and beta-gamma meters

Recommended working conditions for radionuclides of different hazards. For inexperienced personnel, 1/10 of the given values should be applied. 'A' refers to a low activity laboratory, 'B' to a semi-hot laboratory with good ventilation, and 'C' to a high activity laboratory with complete enclosure of the working area (hot laboratory).

Working Space	Radioactivity in millicuries		
	α	β	γ
A. Open laboratory bench (only if (t < 10d) and the sample is dust free)........................	0.1	0.1	0.1
B. Fumehood with stock solutions behind lead shielding..........	0.1	5	5
Fumehood with frontal shield...		5-300	5-100
C. Simple manipulator cell, 10 cm Pb............................		300	100-2 000
Advanced manipulator cell of the master-slave-type.............			2 000
Glove-boxes....................	>0.1		

F. Decontamination Procedures

a. Work area - soak up solutions with tissues, wash area well, checking with survey meter.

b. Personnel - for unbroken skin wash 2-3 minutes with mild soap, repeat as necessary. If necessary use solution of equal volumes of $KMnO_4$ (sat'd) and 0.2 N H_2SO_4 for 2 minutes, rinse with H_2O and then 5% solution $NaHSO_3$ for 2 minutes.

If cut, wash immediately in strong stream of water. For ingestion, treat as for toxic chemicals, induce vomiting.

SECTION V

Problems

1. If a 7.7 MeV α particle is found to have a range of 5 cm in air, estimate the number of ion pairs produced in this interaction.

2. How much energy is lost when an α particle interacts with helium to form 2×10^3 ion pairs?

3. What is the approximate range of a 6.3 MeV α particle in Al? In air?

4. Will the specific ionization per unit path length be greater for heavy particles or electrons?

5. For the interaction of electrons with matter the ratio between energy lost by radiation (such as bremsstrahlung) and ionization is given by

$$\frac{(dE/dx)_R}{(dE/dx)_I} = \frac{EZ}{800}$$

Compare the rate of energy loss by both processes for a 10 MeV electron when lead (Z=82) is used as the absorber.

Problems (cont.)

6. Which of the three mechanisms for the interaction of γ-rays with lead will be dominant if the energy of the γ-ray is 1 MeV? With aluminum?

7. What is the dose in rem received by a worker exposed to a field of radiation which is measured to be 50 mr for gammas? (1 mr=0.001 rad).

8. What is the total accumulated dosage (rems) recommended as the maximum permissible by age 25, 45, 60?