INTRODUCTION TO IONIZING RADIATION

Lecture Outline

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I. **INTRODUCTION**

A. Basic Model of a Neutral Atom.

Electrons(-) orbiting nucleus of protons(+) and neutrons. Same number of electrons as protons; net charge = 0. **Atomic number** (number of protons) determines element. **Mass number** (protons + sneutrons) gives mass in terms of 1/12th mass of Carbon atom.

B. Definition of Ionizing Radiation.

Ionization vs. Excitation: **Excitation** transfers enough energy to an orbital electron to displace it further away from the nucleus. In **ionization** the electron is removed, resulting in an **ion pair** (the newly freed electron(-) and the rest of the atom(+))

Ionizing Radiation: Any electromagnetic or particulate radiation **capable of producing ion pairs** by interaction with matter. **Scope limited** to **X** and **gamma** rays, **alpha** particles, **beta** particles (electrons), **neutrons**, and charged nuclei.

Particularly important biologically since media can be altered (e.g., ionized atom in DNA molecule may be altered, thereby causing cell death, or a change in cell reproduction, division, or mutation).

II. **TYPES OF IONIZING RADIATIONS**

A. General Characteristics

Particulate vs. Electromagnetic Radiations: **Particulate Radiations** are sub-atomic particles with **mass** (e.g., alpha and Beta particles, electrons, neutrons). **EM Radiations** (X-rays and gamma rays) **have no mass** and no charge.

High vs. Low Energy Radiation: Absorption of radiation is the process of transferring the energy of the radiation to the atoms of the media through which it is passing. **Higher energy** radiation of the same type **will penetrate further**. Usually expressed in KeV or MeV (10^3 or 10^6 electron Volts). 1 eV = 1.6×10^{-19} Joules = 1.6×10^{-12} ergs

High vs. Low Linear Energy Transfer (LET) to absorbing material: LET is measured by the ionization density (e.g., ion pairs/cm of tissue) along the path of the radiation. **Higher LET causes greater biological impact and is assigned a higher Quality Factor(QF).** Example QF values: X, gamma, and beta have QF = 1; alpha QF=20; thermal neutrons QF=3; "fast" neutrons (>10 KeV) QF = 10; fission fragments QF>20.

B. Characteristics of Common Radiations

Alpha Particles (or Alpha Radiation): **Helium nucleus** (2 neutrons and 2 protons); +2 charge; heavy (4 AMU). Typical Energy = 4-8 MeV; **Limited range** (<10cm in air; 60µm in tissue); High LET (**QF=20**) causing **heavy damage** (4K-9K ion pairs/µm in tissue). **Easily shielded** (e.g., paper, skin) so& an **internal radiation** hazard. Eventually lose too much energy to ionize; become He.

Beta Particles: High speed **electron ejected from nucleus**; -1 charge, light 0.00055 AMU; Typical Energy = several KeV to 5 MeV; Range approx. 12'/MeV in air, a few mm in tissue; Low LET (**QF=1**) causing **light damage** (6-8 ion pairs/µm in tissue). Primarily an internal hazard, but high beta can be an external hazard to skin. In addition, the high speed electrons may lose energy in the form of X-rays when they quickly decelerate upon striking a heavy material. This is called **Bremsstralung** (or Breaking) **Radiation.** Aluminum and other light (<14) materials and organo-plastics are used for shielding.

Note: Beta particles with an opposite (+) charge are called positrons. These quickly are annihilated by combination with an electron, resulting in gamma radiation (see Pair Production below).

Neutrons: Neutron ejected from a nucleus; 1 AMU; 0 Charge; Free neutrons are unstable and decay by Beta emission (electron and proton separate) with $T_{½}$ of approx. 13 min. Range and LET are dependant on "speed": Slow (<10 KeV), "Thermal" neutrons, **QF=3**, and Fast (>10 KeV), **QF=10**.

Shielded in stages: High speed neutrons are "thermalized" by elastic collisions in hydrogenous materials (e.g., water, paraffin, concrete). The nuclei which are "hit" give off the excess energy as secondary radiation (alpha, beta, or gamma). Slow neutrons are captured by secondary shielding materials (e.g., boron or cadmium).

X- and **Gamma Rays**: **X-rays** are photons (Electromagnetic or EM radiations) emitted **from electron orbits**, such as when an excited orbital electron "falls" back to a lower energy orbit; **Gamma rays** are photons emitted **from the nucleus**, often as part of radioactive decay. Gamma rays typically have higher energy (Mev's) than X-rays (KeV's), but both are unlimited.

No mass; Charge=0; Speed = C; **Long range** (km in air, m in body); **light damage (QF = 1)**; An **external hazard** (>70 KeV penetrates tissue); Usually shielded with lead or concrete (see equation for shielding effectiveness).

Photon Interactions: Three types of indirect ionization caused by EM radiation.

Photoelectric effect: Can occur at low energies (< .5 MeV); incoming photon ejects an electron. ***Compton effect***: Occurs at medium energies (.5 - 5 MeV); incoming photon ejects an electron and a photon with longer wavelength. ***Pair production***: Requires high energies (> 1.02 MeV, usually > 5 MeV); incoming photon ejects an electron and a positron, but positron quickly encounters an electron and annihilates to two 0.51 MeV gamma rays ($E=Mc^2$).

III. **Radioactive Decay**

Matter transforms from **unstable to stable** energy states. **Radioactive materials** are substances which **spontaneously emit** various combinations of ionizing particles (alpha and beta) and gamma rays of ionizing radiation **to become more stable**. This process is called **radioactive decay**. **Radioisotopes** are isotopes (same number of protons but different numbers of neutrons) which are radioactive. **Alpha Decay:** Atomic mass reduced by 4; protons reduced by 2.

Radium → alpha particle + Radon

$^{226}_{88}Ra \rightarrow {}^{4}_{2}He^{+2} + {}^{222}_{86}Rn$

Beta Decay: No change in atomic mass; protons increase by 1. (Note: Consider a neutron as a proton embedded with an electron; net charge = 0. When the electron is ejected, a proton is "created", thus increasing the atomic number.)

Strontium → Beta electron + Y

$^{90}_{38}Sr \rightarrow$ Beta electron $+ {}^{90}_{39}Y$

Series Decay: Radioactive parent decays to a **"daughter"** which may also be radioactive, therefore, is also simultaneously decaying. Resulting exposure is to the combination of both decays (and possibly additional daughters). Radon daughters are an important example of series decay exposure in uranium mines and basements.

IV. **QUANTIFICATION OF RADIATION**

A. Quantifying Radioactive Decay

Measurement of **Activity** in disintegrations per second (dps); 1 **Becquerel** (Bq) = 1 dps; 1 **Curie** (Ci) = 3.7×10^{10} dps; Activity of substances are expressed as activity per weight or volume (e.g., Bq/gm or Ci/l).

Simple Decay Equations (see example problems 1,2)

$A_t = A_o e^{(-\boldsymbol{\lambda} \times t)}$ = Activity after time t

$N_t = N_o e^{(-\boldsymbol{\lambda} \times t)}$ = Number of atoms ater time t

$\boldsymbol{\lambda} = 0.693/T_{½}$ = disintegration constant

Where:
A_o = Original activity
N_o = Original atoms
$T_{½}$ = Half-Life = time to reduce to half the original

B. Quantifying Exposure and Dose

Exposure: **Roentgen**

1 Roentgen (R) = amount of **X or gamma** radiation that produces ionization resulting in 1 electrostatic unit (esu) of charge in 1 cm^3 of dry **air** at STP. Instruments often measure exposure rate in mR/hr.

Absorbed Dose: **rad**

1 rad (Roentgen absorbed dose) = absorption of 100 ergs of energy from **any radiation** in 1 gram of **any material**; 1 **Gray** (Gy) = 100 rads = 1 Joule/kg; Exposure to 1 Roentgen approximates 0.9 rad in air.

Dose (in rads) = 0.869(f)(Roentgens) where the f-factor is the ratio of mass energy-absorption coefficient of medium, such as bone, compared to air.

Biologically Equivalent Dose: **rem**

Rem (Roentgen equivalent man) = dose in rads x QF, where QF = quality factor. 1 **Sievert** (Sv) = 100 rems.

C. Exposure Limits

Regulatory Agencies: OSHA, personnel exposures (29 CFR 1910.96, 1910.120); Nuclear Regulatory Commission, (10 CFR 19, 20, and 71); Dept of Transportation, (49 CFR). Most advocate **ALARA** - As Low As Reasonably Achievable.

OSHA Limits: Whole body limit = 1.25 rem/qtr or **5 rem (50 mSv) per year** (approx. 2.5 mrems/hr for all work hours). Hands and feet limit = 18.75 rem/qtr. Skin of whole body limit = 7.5 rem/qtr. Total **life accumulation = 5 x (N-18) rem where N = age**. Can have 3 rem/qtr if total life accumulation not exceeded. Restricted areas at 200 mrem/hr. Posting at 200 and 100 mrem/hr. Note: New recommendations reduce the 5 rem to 2 rem.

Working Level Month(WLM): Unit of exposure to Radon progeny in uranium mines. 1 **Working Level Month (WLM)** = exposure to 1 Working Level (1.3 x 10^5 MeV of alpha energy) for one month; roughly 100 pC/l.

Hazardous Waste Sites: Radiation above background (0.01-0.02 mrem/hr) signifies possible presence which must be monitored. Radiation above 2 mrem/hr indicates potential hazard. Evacuate site until controlled.

V. **HEALTH EFFECTS**

Generalizations: Biological effects are due to the ionization process that destroys the capacity for cell reproduction or division or causes cell mutation. The effects of one type of radiation can be reproduced by any other type. A given total dose will cause more damage if received in a shorter time period. A **fatal dose (600 R)** causes a temperature rise of only 0.001 C, and ionization of 1 atom in 100 million.

Acute Somatic Effects: Relatively immediate effects to a person acutely exposed. Severity depends on dose. Death usually results from damage to bone marrow or intestinal wall. Acute **radiodermatitis** is common in radiotherapy; chronic cases occur mostly in industry.

ACUTE DOSE(RAD) EFFECT

0-25	No observable effect.
25-50	Minor temporary blood changes.
50-150	Possible nausea and vomiting and reduced WBC.
150-300	Increased severity of above and diarrhea, malaise, loss of appetite. Some death. Increased severity of above and hemorrhaging, depilation. LD_{50} at 450-500 rads.
300-500	Symptoms appear sooner. LD_{100} approx. 600 rads.
> **500**	

Delayed Somatic Effects: Delayed effects to exposed person include: Cancer, leukemia, cataracts, life shortening from organ failure (not directly observed in man), and abortion. Probability of an effect is proportional to dose (no threshold). Severity is independent of dose. Doubling dose for cancer is approximately 10-100 rems.

Genetic Effects: Genetic effects to off-spring of exposed persons are irreversible and nearly always harmful. Doubling dose for mutation rate is approximately 50-80 rems. (Spontaneous mutation rate is approx. 10-100 mutations per million population per generation.)

Critical Organs: Organs generally most susceptible to radiation damage include: Lymphocytes, bone marrow, gastro-intestinal, gonads, and other fast-growing cells. The central nervous system is resistant. Many nuclides concentrate in certain organs rather than being uniformly distributed over the body, and the organs may be particularly sensitive to radiation damage, e.g., isotopes of iodine concentrate in the thyroid gland. These organs are considered "critical" for the specific nuclide. *RBE Relative Biological Effectiveness*: Ratio that compares the effect on standard cells to the effect of test cells.

VI. **SOURCES**

General Population Exposure: Average Annual Dose is approx. **200-300 mrem per year** from Medical(100 mrem), Radon(100+), Terrestrial(55), Cosmic(30), Fallout(4), Industrial(<1). Internal (e.g., K^{40}, Ra^{226}, Pb^{210}, Rn^{22}, C^{14}) varies with target organs, typically < 20mrem (**K^{40}** alone accounts for most).

Occupational Exposures (Examples): Naturally occurring radioactive materials, such as radon in mining, but many are in sealed sources for protection (see below); industrial and medical radioisotopes, such as tracer elements; High Voltage devices such as X-ray machines, Radar generators, VDT's and TV's; nuclear reactors.

Sealed Source: Radioactive material that is permanently bonded or fixed in a capsule or matrix designed to prevent release of the material under the most severe conditions of normal use and handling.

High Voltage Devices: The electric fields of high voltage (> 10 KV) devices, such as television and radar klystron tubes, can accelerate electrons to a high speed such that they escape their orbitals, resulting in an ion pair.

Nuclear Reactions: Nuclear fission (splitting atoms, e.g., nuclear weapons) and fusion (combining atoms, e.g., the sun combines two H's into He) both result in the release of energy (radiation).

Neutron bombardment is used to inject an extra neutron into an otherwise stable atom, thus producing an unstable radionuclide. Neutron emission usually occurs in industry when a light weight element is bombarded with alpha particles or gamma rays, as shown:

With alpha = ${}^{9}_{4}Be + {}^{4}_{2}He^{+2} \rightarrow {}^{1}_{0}\text{neutron} + {}^{12}_{6}C$

With photon = ${}^{9}_{4}Be + \text{photon} \rightarrow {}^{1}_{0}\text{neutron} + {}^{8}_{4}Be$

VII. **RADIATION CONTROLS**

A. Basic Control Methods for External Radiation

Time: Minimize time of exposure to minimize total dose. Rotate employees to restrict individual dose.

Distance: Maximize distance to source to maximize attenuation in air. The effect of distance can be estimated from the following equations:

- Estimating Intensity near the Source

$D = \Gamma A / d^2$

D = Exposure rate (R/hr)

Γ = Specific gamma ray constant in units of $^{R \cdot cm2}/_{mCi \cdot hour}$

d = distance from source in cm

A = Activity in mCi of the isotope

- Estimating Attenuation in Air Using **Inverse Square Law**

$I_2 = I_1 [d_1 / d_2]^2$

I_2, I_1 = Intensity at d_2, d_1

d_2, d_1= Distance to source

Shielding: Minimize exposure by placing absorbing shield between worker and source. The following estimates the effectiveness of shielding.

$I = I_o B e^{-\mu x}$ = intensity on other side of shield

Where:

I_o = original intensity
μ= linear absorption coefficient for material
x = shield thickness (same units as #u)
B = radiation scatter "build up" factor (Assume B = 1)

Half-Value Layer (HVL): The shield thickness necessary to reduce intensity by half. HVL = 0.693 / μ. Similarly, a tenth-value layer reduces intensity by 10.

B. Monitoring

Personal Dosimeters: Normally they do not prevent exposures (no alarm), just record it. They can provide a record of **accumulated exposure** for an individual worker over extended periods of time (hours, days or weeks), and are small enough for measuring localized exposures (e.g., ring badges). Common types: Film badges; Thermoluminescence detectors (TLD); and pocket dosimeters.

Direct Reading Survey Meters and Counters: Useful in **identifying source** of exposures recorded by personal dosimeters, and in **evaluating potential sources,** such as surface or sample contamination, source leakage, inadequate decontamination procedures, background radiation. Some can be used to evaluate IH samples (e.g., air, bulks, wipes). Common types:

Alpha	**Proportional or Scintillation counters**
Beta, Gamma	**Geiger-Mueller or Proportional counters**
X-ray, Gamma	**Ionization chambers**
Neutrons	**Proportional counters**

Continuous Monitors: Continuous direct reading ionization detectors (same detectors as above) can provide read-out and/or alarm to monitor hazardous locations and alert workers to leakage, thereby **preventing exposures**.

Long-Term Samplers: Used to measure average exposures over a longer time period. For example, charcoal canisters or electrets are set out for days to months to measure radon in basements (should be <4 pCi/L).

C. Example Elements of Radiation Protection Program

Identification and inventory of sources. (Note: Isotopes are classified as to relative radiotoxicity from **Class 1, Very high, to Class 4, slight toxicity.**) Including analysis of reports of inspections and accidents.

Monitoring of exposures: Personal, area, and screening measurements; Medical/biologic monitoring. (Note: NRC requires reporting of exposures > PEL within 30 days, > 5 rem within 24 hrs, and > 25 rem immediately.)

Task-Specific Procedures and Controls: Initial, periodic, and post-maintenance or other non-scheduled events. Engineering (shielding) vs. PPE vs. administrative controls. Including management and employee commitment and authority to enforce procedures and controls.

Emergency procedures: Response, "clean-up", post clean-up testing.

Training and Hazard Communications including signs, warning lights, lockout/tagout, etc. Criteria for need, design, and information given.

Material Handling: Receiving, inventory control, storage, and disposal.

Note: **DOT Shipping Limits**:	*Label Color*	*Surface*	*1 Meter*
	White Rad I	0.5	0
(mR/hr)	Yellow Rad III	10	0.5
	Yellow Rad III	200	10

D. Example from Requirements of 29 CFR 1910.120 Related to Ionizing Radiation
Monitoring with direct reading instruments; **Risk identification; Employee notification** prior to work; **Engineering controls, work practices**, and **PPE** for employee protection; Drums and containers containing radioactive wastes shall not be handled until their hazard to employees is properly assessed; and **Decontamination.**

Attachment 1. Ionizing Radiation Equations
Attachment 2. Example Problems
Attachment 3. Ionization
Attachment 4. EM Interaction
Attachment 5. Radio Active Decay Series
Attachment 6. Maximum Permissible Dose Equivalent for Occupational Exposure
Attachment 7. X-Ray Tube
Attachment 8. Radioactive Isotopes
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Attachment 10. Tank Level Detector
Attachment 11. Principal Isotopes in Sealed Sources
Attachment 12. Example of Half-Value Layers
Attachment 13. Shielding Layer Examples
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