# Algebra-Based Physics-2: Electricity, Magnetism, and Modern Physics (PHYS135B-01): Unit 5

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November 28, 2023

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# Nuclear physics in medicine: Biological effects of ionizing radiation

Ionizing radiation affects molecules within cells, particularly DNA molecules.

**Ionizing radiation** is any radiation from (for example) radioactive isotopes that deposits enough energy in matter to free bound electrons from atoms.

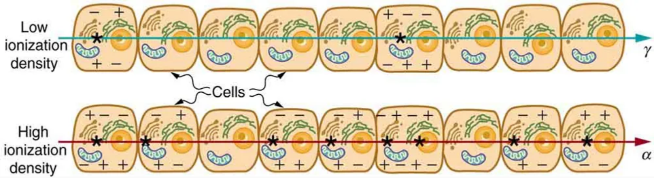


Figure 1: Different classes of ionizing radiation affect cell tissue differently.

Ionizing radiation affects DNA molecules. The energy required to break a hydrogen bond is 21 kJ/mole (in $H_2O$). This is $< 1$ eV per atom.

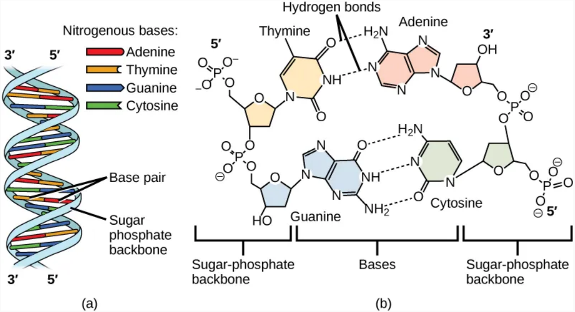


**Figure 2:** DNA is a molecule with double-helix structure, a sugar-phosphate backbone, and nucleic acid base-pairs bound with hydrogen bonds.

# Nuclear medicine: Biological effects of ionizing radiation

Ionizing radiation affects DNA molecules. The energy required to break a hydrogen bond is 21 kJ/mole (in $H_2O$). This is $< 1$ eV per atom.

1. DNA is *self-healing*, containing code that checks for errors and code for repair.
2. A typical damage rate is $\approx 1$ million errors per cell per day. The response rate depends on cell type and age.
3. Three outcomes after excess damage:
   - Senescence: a state of irreversible dormancy
   - Pre-programmed cell death
   - Unregulated cell division leading to tumors and cancers
4. Cancer is unregulated cell division, which can be both caused and stopped by radiation.

# Nuclear medicine: Biological effects of ionizing radiation

| Unit | Definition | Purpose |
| --- | --- | --- |
| 1 rad | 0.01 J/kg | Quantifies deposited ionization energy |
| 1 Gray (Gy) | 100 rad | Quantifies deposited ionization energy |
| RBE[1] | Varies by radiation | Quantifies ionization concentration |
| rem[2] | rad $\times$ RBE | Quantifies health effects of radiation |
| 1 Sv (Sievert) | Gy $\times$ RBE, 100 rem | Quantifies health effects of radiation |

**Table 1:** Common units involved in assessing ionizing radiation in the human body.

[1] Relative biological effectiveness
[2] roentgen equivalent man

| Type and energy of radiation | RBE[1] |
|---|---|
| X-rays | 1 |
| $\gamma$ rays | 1 |
| $\beta$ rays greater than 32 keV | 1 |
| $\beta$rays less than 32 keV | 1.7 |
| Neutrons, thermal to slow (<20 keV) | 2–5 |
| Neutrons, fast (1–10 MeV) | 10 (body), 32 (eyes) |
| Protons (1–10 MeV) | 10 (body), 32 (eyes) |
| $\alpha$ rays from radioactive decay | 10–20 |
| Heavy ions from accelerators | 10–20 |

Figure 3: The RBE factors for different classes of radiation. Note that the most common radiation classes have RBEs of 1, so rem = rad, and 1 Sy = 1 Gy. The RBE for $\alpha$ radiation is significantly higher due to shorter, more concentrated range in tissue.

# Nuclear medicine: Biological effects of ionizing radiation

| Quantity | SI unit name | Definition | Former unit | Conversion |
|---|---|---|---|---|
| Activity | Becquerel (bq) | decay/s | Curie (Ci) | $1 \text{ Bq} = 2.7 \times 10^{-11} \text{ Ci}$ |
| Absorbed dose | Gray (Gy) | 1 J/kg | rad | $\text{Gy} = 100 \text{ rad}$ |
| Dose Equivalent | Sievert (Sv) | 1 J/kg × RBE | rem | $\text{Sv} = 100 \text{ rem}$ |

Figure 4: The distinction between activity, and absorbed dose and dose equivalent.

# Nuclear medicine: Biological effects of ionizing radiation

| Dose in Sv [2] | Effect |
|---|---|
| 0–0.10 | No observable effect. |
| 0.1 – 1 | Slight to moderate decrease in white blood cell counts. |
| 0.5 | Temporary sterility; 0.35 for women, 0.50 for men. |
| 1 – 2 | Significant reduction in blood cell counts, brief nausea and vomiting. Rarely fatal. |
| 2 – 5 | Nausea, vomiting, hair loss, severe blood damage, hemorrhage, fatalities. |
| 4.5 | LD50/32. Lethal to 50% of the population within 32 days after exposure if not treated. |
| 5 – 20 | Worst effects due to malfunction of small intestine and blood systems. Limited survival. |
| >20 | Fatal within hours due to collapse of central nervous system. |

Figure 5: As the dose equivalent increases (measured in Sv), the health effects become qualitatively more dangerous.

What is the dose (in rad) if 100 mJ of total energy is deposited in the body of a 50 kg adult male?

- A: 0.2 rad
- B: 2.0 rad
- C: 20.0 rad
- D: 200.0 rad

If the above dose was instead concentrated in 1.0 kg of brain tissue, what would be the dose in rad?

- A: 0.1 rad
- B: 1.0 rad
- C: 10 rad
- D: 100 rad

If the RBE is 1 because we are dealing with x-rays, is the **equivalent dose** fatal? Answer: rem = rad, because RBE = 1, then convert to Sv and use Tab, 5.

# Nuclear medicine: Biological effects of ionizing radiation

What is the equivalent dose (in Sv) if 500 mJ of total energy is deposited by $\alpha$ radiation (RBE of 20) in the 1 kg lungs of an adult male?

- A: 0.1 Sv
- B: 1.0 Sv
- C: 10.0 Sv
- D: 50.0 Sv

What can be said about the probability of survival?

- A: $>$50 percent.
- B: $<$50 percent.
- C: It is unknown.
- D: It is 100 percent.

*The person is at risk [for cancer] for at least 30 years after the latency period … the overall risk of a radiation-induced cancer death per year per rem of exposure is about 10 in a million …* $10/10^6$ *rem*$^{-1}$ *yr*$^{-1}$.

*If a person receives a dose of 1 rem, his risk each year of dying from radiation-induced cancer is 10 in a million and that risk continues for about 30 years. The lifetime risk is thus 300 in a million, or 0.03 percent. Since about 20 percent of all worldwide deaths are from cancer, the increase due to a 1 rem exposure is impossible to detect demographically. But 100 rem (1 Sv), which was the dose received by the average Hiroshima and Nagasaki survivor, causes a 3 percent risk, which can be observed in the presence of a 20 percent normal or natural incidence rate.*

Suppose a woman receives an x-ray, and there is an incidental exposure of 25 rem to her breast tissue. What is her increased lifetime risk of breast cancer due to the exposure?

- A: 75 percent
- B: 7.5 percent
- C: 0.75 percent
- D: 25 percent

If we receive 3.5 mrem (milli-rem) per plane flight from cosmic rays, how many flights can we take before we reach 1 Sv?

- A: 17
- B: 33
- C: 63
- D: 286

# Nuclear medicine: Biological effects of ionizing radiation

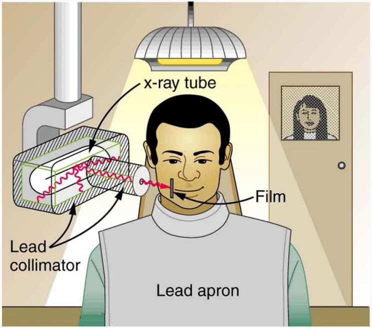


Figure 6: Suppose this dental x-ray source has an **activity** of 1 Curie, or $37 \times 10^9$ Bq. Recall that 1 Bq is 1 particle per second in the context of radiation.

**Group exercise:** Assume the energy of each x-ray is 70 keV, and the exposure lasts 3.5 seconds. Determine the effective dose in mrem to the patient, if the affected tissue has a mass of 1.5 kg.

# Nuclear physics in medicine: Therapeutic uses of ionizing radiation

# Nuclear medicine: Therapeutic uses of ionizing radiation

Ionizing radiation may be used to treat cancer.

- `https://xkcd.com/881/`
- `https://xkcd.com/931/`
- `https://xkcd.com/933/`
- `https://xkcd.com/1217/`

**Figure 7:** Que descanse en paz, suegro.

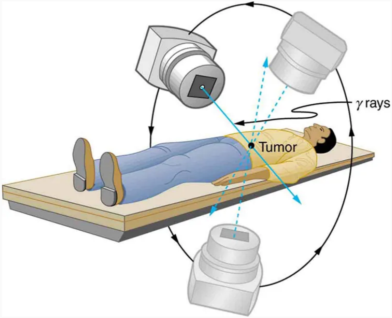


**Figure 8:** A $\gamma$ ray cannon is rotated around the patient.

Treatments maximize the **therapeutic ratio**, the ratio of exposure to tumor versus exposure to healthy tissue.

# Nuclear medicine: Therapeutic uses of ionizing radiation

Ionizing radiation may be used to treat cancer.

| Type of Cancer | Typical dose (Sv) |
|---|---|
| Lung | 10–20 |
| Hodgkin's disease | 40–45 |
| Skin | 40–50 |
| Ovarian | 50–75 |
| Breast | 50–80+ |
| Brain | 80+ |
| Neck | 80+ |
| Bone | 80+ |
| Soft tissue | 80+ |
| Thyroid | 80+ |

**Figure 9:** The equivalent doses of radiation for different cancer tissues.

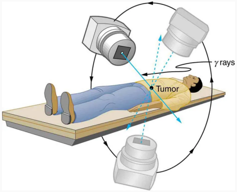


**Figure 10:** A $\gamma$ ray cannon is rotated around the patient.

Treatments maximize the **therapeutic ratio**.

# Nuclear medicine: Therapeutic uses of ionizing radiation

Recall that the intensity of ionizing radiation through matter goes as

$$I(z) = I_0 e^{-\sigma_{\mathrm{tot}} n z} \quad (1)$$

and that half of the intensity is stopped by the matter after a distance

$$z_{1/2} = \frac{\ln 2}{\sigma n} \quad (2)$$

**Group exercise:** The treatment in Fig. 11 involves $^{60}$Co $\gamma$ rays with energies of 1.173 and 1.332 MeV. Suppose that $I_0 = 10^{12}$ Bq cm$^{-1}$, and that $(\sigma n) = 0.1$ cm$^{-1}$ in tissue, **implying that $5I_0$ (in Bq) are deposited in the first 10 cm of tissue**. Using the higher energy, compute the effective dose (RBE = 1) for a 90 second exposure to the 1 kg of tissue in the first 10 cm. *Answer:* $\approx$ *60 Sv.*

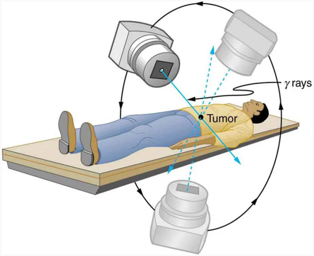


**Figure 11:** What will be the equivalent dose?

**Instructor:** demonstrate how we find $5I_0$ for the first 10 cm.

# Nuclear physics in medicine: Food irradiation

# Nuclear physics in medicine: Food irradiation

**Ionizing radiation may be used to improve food quality.**

- Food irradiation is not widely accepted.
- Pros: replaces pasteurization, preservatives, and insecticides
- Cons: potentially toxic residues, environmental hazards
- Could increase crop production by 25%, and reduce food spoilage by 25%.
- Currently, in USA we use it on spices, some fruits. Approved in 40 countries.

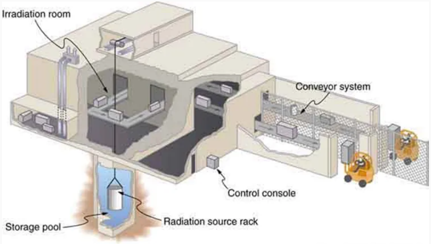


**Figure 12:** A $\gamma$ ray food irradiation plant.

**Types of radiation:** $^{60}$Co or $^{137}$Cs $\gamma$ rays (MeV), x-rays (100 keV), electrons (10 MeV).

**Typical doses:** *Low-dose*: 1000 Gy, kills many microorganisms on fresh produce. *High-dose*: 10,000 Gy, kills bacteria like salmonella, more required for fungi.

# Nuclear physics in medicine: Food irradiation

**Group exercise:** Suppose the water container for the $\gamma$ rays is a cylindar with a radius of 5 m and height of 10 m. Suppose that the $\gamma$ ray cross-section in water at 1 MeV is $\approx 1$ barn. Use Eq. 1, with $\sigma = 1$ barn $= 10^{-28}$ m$^2$ and $n = 0.33 \times 10^{29}$ m$^{-3}$ to compute the fraction of $\gamma$ rays that survive after 5 m and 10 m of water.

*Answers: for 5 m, the probability is* $6 \times 10^{-8}$. *For 10 m, it is* $3 \times 10^{-15}$. *(Assume a food mass of 1 kg, and* $10^4$ *Sv). When not in use, the* $\gamma$ *source causes 180* $\gamma$ *rays to escape into the rock after 10 m of water. Then the* $\gamma$ *rays are blocked by rock.*

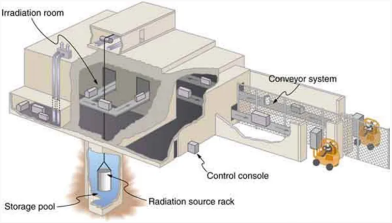


Figure 13: A $\gamma$ ray food irradiation plant.

# Conclusion

# Unit 5 Summary

1. Electromagnetic waves - Chapters 24.1 - 24.4
    - Maxwell's Equations
    - Electromagnetic wave production
    - Electromagnetic spectrum and energy
2. Geometric optics - Chapters 25.1 - 25.3, 25.6
    - Ray-tracing and reflection
    - Refraction
    - Lens optics

# Unit 5 Summary

1. Wave optics - Chapters 27.1 - 27.3
    - Wave interference
    - Wave diffraction
    - Double slit experiments
2. Nuclear physics in medicine - 32.1 - 32.4
    - Diagnostics and medical imaging
    - Biological effects of ionizing radiation
    - Therapeutic uses of ionizing radiation
    - Food irradiation