

# Chapter (31)

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## Revision

$$N = N_0 e^{-\lambda t}$$

$$\checkmark R = \underline{N} \lambda$$

$$\checkmark R = \underline{N_0} e^{-\lambda t} \lambda$$

$$T_{1/2} = \frac{0.693}{\lambda}$$

$$\checkmark R = R_0 e^{-\lambda t}$$

# Chapter 31

## Nuclear Energy; Effects and Uses of Radiation

### Lecture 1

The University of Jordan/Physics Department

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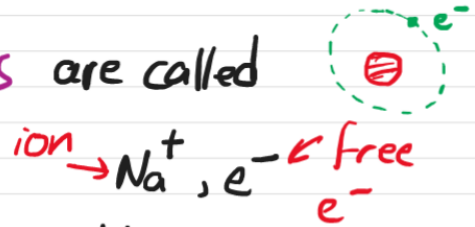
31-4] Passage of radiation through; biological damage  
↳ through Matter

Nuclear radiation includes :

${}^4_2\text{He}^{++}$  —  $\alpha, \beta^+, \beta^-, p, n, \pi, \gamma, \dots$

X-rays are also a type of radiation but **NOT** nuclear radiation as x-rays don't originate from the nucleus. X-rays are emitted from transitions of electrons between atomic energy levels.

Nuclear radiation and x-rays are called ionizing radiation. Why?



When radiation passes through matter it ionizes the atoms (produce free  $e^-$  and positive ions).

When radiation passes through matter it can cause considerable damage.

Metals and structural materials become brittle and become weakened due to passage of radiation.

### Biological Damage

Damage of biological cells is primarily due to the ionization that is caused by the radiation.

- Free electrons and positive ions can interfere with the normal operations of the cell like, for example, important chemical reactions.
- knocking electrons off atoms and molecules (ionization) can break molecules and may also change their structure which eventually interferes with the normal functions of the cell.

- Radiation may also damage the DNA. Each alteration to the DNA can affect a gene and alter the molecule it codes for.

### 31-5] Measurement of Radiation-Dosimetry

Controlled amount of radiation can be used for diagnosis and also for treatment of cancer. Radiation is used to kill malignant (cancerous) cells.

Therefore, it is important to quantify the amount or dose of radiation. This is known as dosimetry.

The strength of a radioactive source is specified by stating its activity at a given time. Remember

$$A = A_0 e^{-\lambda t}$$

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Therefore, activity decreases with time. Therefore, we must state the time when we specify the activity particularly when the radioactive source has a short half-life.

SI unit of activity is the Becquerel (Bq)

$$1 \text{ Bq} = 1 \text{ decay/s}.$$

Another more commonly used unit is the Curie (Ci)

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq (decays/s)}.$$

1 Ci is the activity of exactly one gram of radium.

Note that activity gives the number of decays per second. But it gives NO information regarding the effect of radiation on biological tissues.

### Exposure

Measured in units of Roentgen (R).

1 Roentgen: Amount of X-rays or  $\gamma$ -radiation that deposits  $0.878 \times 10^{-2} \text{ J}$  of energy per kg of air.

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1 Roentgen: Amount of X-rays or  $\gamma$ -radiation that deposits  $0.878 \times 10^{-2}$  J of energy per kg of air.

NOTE: The definition of exposure has limited

- ① radiation type to X-rays and  $\gamma$ -radiation.
- ② matter where energy is deposited to air. [nothing about biological tissues or the effect of radiation on biological tissues].

# Chapter 31

## Nuclear Energy; Effects and Uses of Radiation

### Lecture 2

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#### Absorbed Dose (AD)

The energy deposited per kg in any medium by any radiation type.

$$AD = \frac{10\text{J}}{100\text{kg}} = 0.1 \frac{\text{J}}{\text{kg}} = 0.1 \text{Gy} = 10 \text{rad}$$

units: Grey (Gy) or Rad

$$1\text{Gy} = 1\text{J/kg}$$

$$\frac{2\text{J}}{50\text{kg}} = \frac{1}{25} \text{Gy} = 0.04 \text{Gy} = 0.04 \text{J/kg}$$

$$1\text{Rad} = 0.01\text{J/kg} \Rightarrow 1\text{Gy} = 100 \text{rad}.$$

Note that AD applies to any radiation and any matter.

$$AD = 0.5 \text{ Gy}, m = 60 \text{ kg} \Rightarrow AD = 0.5 \frac{\text{J}}{\text{kg}}$$

Question:

$$\text{energy absorbed} = 0.5 \frac{\text{J}}{\text{kg}} \times 60 \text{ kg} = 30 \text{ J}$$

Which is more dangerous to living tissues, an absorbed dose of 1 Gy of

alpha radiation OR 1 Gy of gamma radiation? (Note the same absorbed dose but the radiation is different)

$$\frac{10 \text{ J}}{10 \text{ kg}} = 1 \text{ Gy}$$

In fact absorbed dose does not quantify the danger of a given radiation to living tissues. Therefore, we need a better assessment!



Effective Dose (ED)

$$ED = AD \times RBE$$

AD ← dose  
↑  
absorbed



**RBE:** relative biological effectiveness of a given type of radiation defined as the number of rads of X-rays or  $\gamma$ -radiation that produces the same biological damage as 1 rad of the given radiation.

Radiation Type	RBE
X- and $\gamma$ rays	1
$\beta$ (electrons)	1
Protons	2
Slow neutrons	5
Fast neutrons	$\approx 10$
$\alpha$ particles and heavy ions	$\approx 20$

1 rad of  $\alpha$ -particles

For  $\alpha$ -particles  $RBE = 20$ .

$$1 \text{ rad} = 0.01 \frac{\text{J}}{\text{kg}}$$

This means that 1 rad of  $\alpha$ -radiation produces the same biological damage as 20 rads of X-rays or  $\gamma$ -rays.



## Units

AD

ED

Gray (Gy)

Sievert (Sv)

Rad

rem

$$ED = AD \times RBE$$

has No unit  
↓  
Sv ← Gy  
rem ← Rad

Since  $1 \text{ Gy} = 100 \text{ rad}$

⇒  $1 \text{ Sv} = 100 \text{ rem}$

Note that RBE has NO dimensions (No units).

## Human exposure to radiation

We are constantly exposed to radiation coming from different sources; like:

- Cosmic rays
- natural radioactivity in rocks and soil.

Upper limit Effective Dose per person per year in the US:

From natural radioactive background: 300 mrem

From X-rays and scans:  $\approx 60$  mrem

Additional allowed in US 100 mrem

Maximum Total allowed in US  $\approx 460$  mrem = 4.6 mSv

Upper limit Effective Dose per person per year for radiation workers (hospitals, power plants, research):  $\approx 20$  mSv

Such workers wear badges called TLD (thermoluminescent dosimeter) to monitor the radiation levels workers are exposed to.

Large doses of radiation cause symptoms like: nausea, fatigue and loss of body hair. In general called radiation sickness. Very large doses can be fatal. A dose of 10 Sv over a short period is usually fatal.

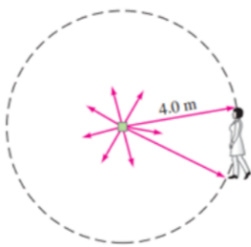


FIGURE 31-16 Radiation spreads out in all directions. A person 4.0 m away intercepts only a fraction: her cross-sectional area divided by the area of a sphere of radius 4.0 m. Example 31-12.

As we move further away from the radiation source, our bodies will be exposed to lesser amounts of radiation.

Intensity of radiation (Energy/unit area) is proportional to  $\frac{1}{r^2}$ .

$$\frac{\text{Energy intercepted by her body}}{\text{total radiate energy}} = \frac{\text{Surface area of her body}}{\underbrace{4\pi r^2}_{\text{surface area of the sphere}}}$$

### Example 31-11]

Limiting the dose.

A worker in an environment with a radioactive source is warned that she is accumulating a dose too quickly and will have to lower her exposure by a factor of ten to continue working for the rest of the year. If the worker is able to work farther away from the source, how much farther away is necessary?

Intensity  $\propto \frac{1}{r^2}$ , need a reduction by a factor of 10.

$I \rightarrow \frac{I}{10} \Rightarrow$  If she is 4m away from the source

$\Rightarrow I \rightarrow \frac{I}{(4)^2} = \frac{I}{16}$ . This is a reduction of more than a factor of 10.

$$\frac{1}{r^2} \geq \frac{1}{10}$$

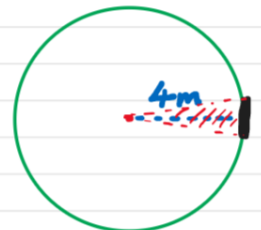
### Example 31-12]

Whole-body dose.

What whole-body dose is received by a 70-kg laboratory worker exposed to a 40-mCi  $^{60}_{27}\text{Co}$  source, assuming the person's body has cross-sectional area  $1.5\text{m}^2$  and is normally about 4.0 m from the source for 4.0 h per day?  $^{60}_{27}\text{Co}$  emits rays of energy 1.33 MeV and 1.17 MeV in quick succession. Approximately 50% of the rays interact in the body and deposit all their energy. (The rest pass through.)

Note The radiation that passes through the body of the worker ( $E_{\text{worker}}$ ) is only a fraction of the total energy ( $E_{\text{tot}}$ ) emitted by the source.

$$\frac{E_{\text{worker}}}{E_{\text{tot}}} = \frac{A_{\text{worker}}}{A_{\text{tot}}} = \frac{1.5\text{m}^2}{4\pi(4)^2\text{m}^2}$$



$$\therefore E_{\text{worker}} = 7.5 \times 10^{-3} E_{\text{tot}}$$

$$\text{Energy radiated per decay } E_{\gamma} = (1.33 + 1.17) = 2.5 \overset{10^6}{\text{MeV}} \underset{1.6 \times 10^{-19} \text{ J}}{\downarrow}$$

Total radiated energy per second:

$$E_{\text{tot}} = \underset{\text{activity}}{A} E_{\gamma} = \underbrace{(40 \times 10^{-3} \text{ s}^{-1} \times 3.7 \times 10^{10})}_{\text{how many decays/s}} (2.5 \times 10^6 \times 1.6 \times 10^{-19} \text{ J})$$

$$\therefore E_{\text{tot}} = 5.92 \times 10^{-4} \text{ J/s} \quad \left( \text{total radiated energy by the source each second} \right)$$

Energy deposited in the workers body per second is

$$E = \left(\frac{1}{2}\right) E_{\text{worker}} = \left(\frac{1}{2}\right) (7.5 \times 10^{-3} E_{\text{tot}})$$

$$= \left(\frac{1}{2}\right) (7.5 \times 10^{-3} \times 5.92 \times 10^{-4} \text{ J/s})$$

$$E = 2.22 \times 10^{-6} \text{ J/s}$$

$$AD = \frac{E}{m} = \frac{2.22 \times 10^{-6} \text{ J/s}}{70 \text{ kg}} = 3.17 \times 10^{-8} \left( \frac{\text{J}}{\text{kg}} \right) \times \frac{1}{\text{s}} \quad \text{Gy}$$

$$AD = 3.17 \times 10^{-8} \frac{\text{Gy}}{\text{s}}$$

Absorbed Dose in 4 hours is  $AD_{4h}$

$$AD_{4h} = AD \times (4 \times 60 \times 60s) = 3.17 \times 10^{-8} \frac{Gy}{s} \times 14400s$$

$$AD_{4h} = 4.56 \times 10^{-4} Gy$$

↑ for  $\gamma$   $RBE = 1$

$$\begin{aligned} ED &= AD \times RBE = 4.56 \times 10^{-4} \times 1 = 4.56 \times 10^{-4} Sv \\ &= 0.456 \times 10^{-3} Sv \\ &= 0.456 mSv \\ &= 45.6 mrem \end{aligned}$$

Q5) A 2.0-mCi source of  $^{32}\text{P}$  is implanted in a tumor to give it a 24-Gy dose. The half-life of  $^{32}\text{P}$  is 14.3 days, and 1mCi delivers 10 mGy/min. How long (in min) should the source remain implanted?

- A) 12
- B) 1200
- C) 2400
- D) 300
- E) 800

Q6) Ionizing radiation can be used on meat products to reduce the levels of microbial pathogens. Assume that for refrigerated meat the upper allowed limit is 3.8 kGy. If a beam of electrons, each of energy 1.6 MeV, irradiates 3.0 kg of beef, how many electrons should the beef mass absorb to reach the upper allowed limit?

- A)  $3.8 \times 10^{10}$
- B)  $4.5 \times 10^{10}$
- C)  $3.8 \times 10^{16}$
- D)  $4.5 \times 10^{16}$
- E)  $1.6 \times 10^{10}$

Q7) A biological tissue of mass  $m$  is exposed to 60 rad of alpha radiation. How many rads of slow neutrons can cause the same damage to the same tissues? (For alpha  $RBE=20$ , for slow neutrons  $RBE = 5$ ).

- 1) 240
- B) 300
- C) 60
- D) 360
- E) 1200

Q2) A 55-kg person has absorbed a 20-rad dose. How many joules of energy are deposited in his body?

- A) 1.1
- B) 20
- C) 11
- D) 55
- E) 1100

Q3) The activity of 1 gram of radium  $^{226}_{88}\text{Ra}$  is exactly 1 Ci. The half-life of radium (in years) is:

- A) 226
- B) 1170
- C) 2280
- D) 1580
- E) 1950

Q4) A 70-kg researcher absorbs  $4.5 \times 10^8$  neutrons in a workday, each of energy 1.2 MeV. The relative biological effectiveness (RBE) for these neutrons is 10. What is the equivalent dosage of the radiation exposure for this researcher, in mrem?

- A) 1.2
- B) 0.39
- C) 0.77
- D) 3.7
- E) 12