National Examination May 2016

98-Phys-B1, Radiation Physics

Three (3) Hours Duration

---

# Notes

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer a clear statement of any assumptions made.
2. This is an **Open Book** exam.
3. Any non-communicating calculator is permitted. You must indicate the type of calculator being used, i.e. write the name and model designation of the calculator, on the first left hand sheet, of the exam work book.
4. This exam has 7 questions, for a total of 89 points.
5. You are required to answer only eighty (80) points worth of questions.
   That is, the full mark is **80** points.
6. Total worth of each question is given at the beginning of the question.
7. Duration: Three (3) Hours

---

# Marking Scheme

**Q.1** 12 points: 1 point for each of the 6 parts of (a), 2 points for (b) and 4 points for (c).

**Q.2** 5 points: 3 points for part (a) and 2 points for (b).

**Q.3** 10 points: 4 points for part (a), 3 points for part (b), and 3 points for part (c).

**Q.4** 6 points.

**Q.5** 16 points: (a) 4 points, (b) 4 points, (c) i 4 points and (c) ii 4 points.

**Q.6** 20 points: (a) 8 points, (b) 2 points, (c) 3 points, (d) 3 points, (e) 4 points.

**Q.7** 20 points: 4 points for each part.

QUESTION 1. (12 points)

On March 7, 2016, the Miami Herald reported that "Recent sampling of water in Biscayne Bay found higher than normal levels of tritium leaking" from Turkey Point's cooling canals.

(a) Tritium can be produced in a pressurized water reactor employing light water, such as those of the Turkey Point Nuclear Generating Station, via the following mechanisms:

i. Fast-neutron interaction with control rods or soluble reactivity additives containing $^{10}$B.

ii. Fast-neutron interaction with the $^{14}$N in residual air.

iii. Fast-neutron interaction with the $^{6}$Li impurities in the reactor coolant.

iv. Thermal-neutron interaction with the $^{2}$H in the reactor coolant.

v. Thermal-neutron interaction with the $^{6}$Li impurities in the reactor coolant.

vi. As a product of ternary fission (which produces three fission products, in addition to neutrons). Assume in your answer that $^{39}$Ar is one of the three fission products.

Write the interaction equation for each of the above reactions.

(b) Explain the hazard caused by exposure to tritium, considering its decay process and its half-life.

(c) The above report indicated that "water sampling in December and January found tritium levels up to 215 times higher than normal in ocean water". Efforts to reduce the radiation dose from tritium should be founded on three basic tenets: (i) Justification, (ii) Optimization, and (ii) Dose Limitation.
Explain how would these tenets be applied to reducing the levels of leaking tritium to more acceptable levels.

---

QUESTION 2. (5 points)

A nuclear energy worker was exposed to the following radiation fields within a three-month period:

- Thermal neutrons: 50 $\mu$Gy.
- Fast ($<$ 2 MeV) neutrons: 20 $\mu$Gy.
- Gamma rays: 100 $\mu$Gy.

(a) Estimate the radiation biological dose this worker was exposed to.

(b) Which of the three components of the exposure is worth investing in to reduce the overall worker's biological dose? Justify your answer.

**QUESTION 3.** (10 points)
Planck constant, $h$, is a fundamental constant in radiation physics, and is often referred to as the "quantum of action". It defines:

- Photon energy,
- Photon linear momentum,
- Angular momentum of an electron orbiting an atom, and
- Uncertainty principle.

(a) Define each of the above in terms of $h$.

(b) Through dimensional analysis, derive the dimensions of $h$ in SI units.

(c) Explain how $h$ in each of the above definitions is a "quantum of action".

---

**QUESTION 4.** (6 points)
Pair-production, like any other physical momentum, requires conservation of total energy (including rest-mass energy) and momentum.
In view of the above statement explain why the threshold energy for pair-production in the field of a nucleus is 1.022 MeV, while the threshold energy for pair-production in the field of an electron is 2.044 MeV.

---

**QUESTION 5.** (16 points) The following equation represents a typical thermal-neutron fission:

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{236}_{92}\mathrm{U}^{*} \longrightarrow \mathrm{FF}_1 + \mathrm{FF}_2 + 3\ {}^{1}_{0}\mathrm{n} + \gamma $$

where FF stands for fission fragment.

(a) Explain why energy is released during this reaction.

(b) State (in percentage terms) how this energy is distributed among the reaction products (FF's, neutrons and gamma rays).

(c) Even after the fission process has essentially stopped, a large amount of energy is still produced in the fuel due to radioactive decay.

i. Explain why most fission fragments are radioactive.

ii. State which decay mode, alpha or beta, is most likely for radioactive fission fragments, and for this mode explain why this causes fission products to be more stable.

**QUESTION 6.** (20 points)

The activity recorded as count rate from a freshly produced radioactive substance was as follows:

| Time, $t$ (hr) | Counts, $C$ (per minute) | $\sigma(C)$ | $g = -\ln\left[1 - \frac{C}{C_\infty}\right]$ | $\sigma(g)$ |
|---|---|---|---|---|
| 0 | 1000 | ... | ... | ... |
| 4 | 1150 | ... | ... | ... |
| 8 | 1300 | ... | ... | ... |
| 16 | 1500 | ... | ... | ... |
| 32 | 1900 | ... | ... | ... |
| 48 | 2200 | ... | ... | ... |
| 80 | 2500 | ... | ... | ... |
| 120 | 2800 | ... | ... | ... |
| $\infty$ | 3000 | ... | | |

where $\sigma(x)$ refers to the statistical variability (standard deviation) in $x$.

(a) Fill in the dots in the above table. Hint: Remember the variance combination rule, for $h = f(x)$: $\sigma^2(h) = \left(\frac{\partial h}{\partial x}\right)^2 \sigma^2(x)$, and assume no error in recording time.

(b) What does the count rate at infinite time, $C_\infty = 3000$, physically signify?

(c) Show, within statistical variability, that $g(t) = -\ln\left[1 - \frac{C_2}{C_{2\infty}}\right]$ is a linear function of time.

(d) What is the physical significance of the slope: dg/dt?

(e) Estimate the half-life of the daughter substance that is building up.

**QUESTION 7.** (20 points)

Laser and microwaves, like x-rays and gamma-rays, are electromagentic waves.

(a) Which one of the above forms of radiation has the highest frequency? Justify your answer based on your knowledge of their origin.

(b) Explain why laser and microwaves do not cause ionization, while x- and gamma-rays do.

(c) Compare the attenuation mechanisms of the four forms of radiation (laser, microwaves, x-rays and gamma-rays) as they travel through matter.

(d) Elaborate on the effect of the following factors on reducing the biological damage that may be caused by the above mentioned forms of radiation:

  i. exposure time,
  ii. distance from source, and
  iii. shielding material.

(e) Mirowave ovens are equipped with glass doors with a fine mesh of wires. This arrangement allows visual access to the oven. Can microwaves pass through the holes between the wires? Explain your answer.