National Examination December 2013
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 paper, a clear statement of any assumptions made.
2. This is an **open book exam.**
   Any non-communicating calculator is permitted.
3. ALL questions must be attempted.
4. Total Worth of Exam: 100 points.
5. Duration: Three (3) Hours.

1. Atomic and nuclear structure, isotopes, radioactivity

The most common isotope of carbon is ^{12}C, while a less common isotope is ^{14}C. The latter isotope is the one used in radiocarbon dating.
Using the following information:

Mass of electron = 0.00054858 u
Mass of neutron = 1.008665 u
Mass of proton = 1.007277 u
Mass of ^{13}C = 13.00335 u
Mass of ^{14}C = 14.003241 u

(a) (4 points) Calculate the binding energy per nucleon for each isotope.

(b) (2 points) Calculate the energy needed to add a neutron to ^{12}C to create ^{13}C.

(c) (5 points) ^{14}C is produced in the atmosphere by cosmic rays striking ^{14}N. The resultant ^{14}C decays with a half-life of 5,730 years to ^{14}N. Write the production and decay relationships.

(d) (4 points) A sample tissue of an Egyptian mummy is found to have a $^{14}C/^{12}C$ ratio of 0.000795 times the ratio found in living human tissue today. Estimate the age of the mummy.

2. X-rays, attenuation and absorption in matter, dosimetry
An 60 kV X-ray machine is used to obtain a dental radiograph in a region consisting of layers of 20 mm muscle, 3.5 mm fat and 6.5 mm bone.

   (a) (1 point) What is the maximum photon energy produced by this machine?

   (b) (2 points) Sketch the energy spectrum of the photons produced by this machine.

   (c) (6 points) In an attempt to improve image quality, the technologist increased the applied voltage from 60 kV to 75 kV. With the machine now operating at the increased voltage and for the same exposure time of 0.5 s, determine the change required in the applied current to maintain the same number of photons incident on the radiographic film. Use the data below and assume that the mean X-ray energy is equal to one third ($\frac{1}{3}$) of the peak X-ray energy.

Linear attenuation coefficient in cm^{-1}

Energy	Muscle	Fat	Bone
20	0.808	0.488	4.542
25	0.594	0.379	3.058
30	0.380	0.271	1.573

   (d) (4 points) Would the radiation dose absorbed by the patient in the altered 75 kV imaging arrangement be higher, lower, or same as in the original 60 kV arrangement, given that the number of photons incident on the radiographic film is kept the same? Justify your answer with calculations based on the argument that the absorbed dose is proportional to the number of photons absorbed by the patient and their energy.

   (e) (3 points) How would the absorbed dose be measured in practice?

   (f) (2 points) At the above tabulated energies, what is the dominant mode of interaction for the X-ray photons in the considered material? Justify your answer.

   (g) (2 points) At a given photon energy, explain why bone has a higher attenuation coefficient than muscle and fat.

3. Detection of radiation, radiation instrumentation, radiation protection

The following equation represents a typical fission reaction:

$$n + {}^{235}U \longrightarrow {}^{236}U^{*} \longrightarrow {}^{92}Kr + {}^{142}Ba + 2\,n + \gamma$$

(a) (1 point) What is the neutron energy at which this fission is most probable?

(b) (2 points) Name two types of detectors that are most efficient for measuring the incident neutrons in the above reaction.

(c) (2 points) Sketch the energy spectrum of the neutrons produced by this reaction, indicating the value of the most probable energy.

(d) (2 points) Name a type of detector that can be used to measure the spectrum of the produced fission neutrons, and explain how it works.

(e) (2 points) How is the radiation dose produced by neutrons measured?

(f) (4 points) Describe an effective arrangement to shield against the radiation produced in the above fission reaction: give material and approximate thickness.

(g) (2 points) State (in percentage terms) how this energy is distributed among the reaction products (Kr, Ba, neutrons and gamma rays).

(h) (2 points) The fission products, ^{92}Kr and ^{142}Ba, are unstable. Explain.

(i) (2 points) What is the most likely mode of decay of ^{92}Kr and ^{142}Ba?

4. Non-ionizing radiation

Infrared radiation has a wavelength in the 0.7 - 300 μm range.

(a) (2 points) Determine the corresponding frequency range.

(b) (2 points) How much energy would an infrared photon carry?

(c) (2 points) It takes more than 6 eV to ionize a sodium atom, use this fact to prove that infrared radiation is not an ionizing radiation at least for sodium.

(d) (2 points) How does the energy of an infrared photon change with reflection?

(e) (2 points) How does the energy of a gamma-ray photon change with scattering?

(f) (2 points) Question 4(d) refers to "reflection", while question 4(e) uses "scattering". Is there a difference between the two terminologies? Justify your answer.

5. Radiation safety and standards

National Geographic News reported on August 21, 2013:

> In the latest crisis to strike the Fukushima-Daiichi nuclear power plant in Japan, operator Tokyo Electric Power (TEPCO) has discovered that 300 tons (nearly 72,000 gallons) of highly radioactive water has leaked from a holding tank into the ground over the past month.
>
> The new storage tank leak presents a different and potentially more serious problem than the ongoing groundwater flow leaks. The water from the leaking tank is so heavily contaminated with strontium-90, cesium-137, and other radioactive substances that a person standing less than two feet away would receive, in an hour's time, a radiation dose equivalent to five times the acceptable exposure for nuclear workers, Reuters reported.

(a) (1 point) Give the value of the "radiation dose equivalent to five times the acceptable exposure for nuclear workers".

(b) (2 points) The above news items explicitly names two fission products and groups the rest under other. Why are the stated radionucluides most relevant?

(c) (2 points) Both ^{129}I and ^{131}I are produced by fission and are of concern following the occurrence of a reactor accident, yet they were not explicitly mentioned in the above news item. Explain.

(d) (2 points) Some news reports indicated that tritium is present in this holding tank. What would cause the presence of tritium, given that it is not a fission product?

(e) The half-life of ^{90}Sr is 29.1 years. It decays by beta emission to ^{90}Y, which in turn decays with a half-life of 64 hours to stable zirconium.

i. (2 points) How long will it take for ^{90}Sr to practically vanish from the ground?

ii. (2 points) Given that both ^{90}Sr and its daughter ^{90}Y are beta emitters, and that beta particles are easily absorbed in soil, why is ^{90}Sr considered a radiological hazard?

(f) The half-life of ^{137}Cs is 30 years. It decays by beta and gamma emission to ^{137m}Ba.

i. (2 points) Whole-body counting can be used to determine exposure to ^{137}Cs but not to ^{90}Sr. Comment on the validity of this statement.

ii. (2 points) After ^{90}Sr practically vanishes from the ground, how much would be left of ^{137}Cs?

6. Radioactivity, dosimetry

Graves is an autoimmune disease that causes thyroid's overactivity. This disease is treated with ^{131}I. A patient received 100 MBq of this isotope, which had a radiological half-life of eight (8) days and a biological half-life of two (2) days. The thyroid's uptake is 60%, and the uptake of the isotope can be assumed to be immediate. Assume that the mean beta and gamma energies per disintegration of ^{131}I are 192 keV and 370 keV, respectively. The dose rate in an infinitely large homogeneous tissue containing a uniform distribution of ^{131}I at an activity of 1 Bq/kg is 27.72×10^{-15} kg Sv/(Bq s) for beta rays and 48.55×10^{-15} kg Sv/(Bq s) for gamma rays. The weight of the patient's thyroid is estimated to be 20 g.

(a) (2 points) Why is iodine used to treat a thyroid disease?

(b) (3 points) How long will it take for the activity of ^{131}I in the body to decrease to one-quarter ($\frac{1}{4}$) of its initial value.

(c) (2 points) Determine the cumulative (integral) activity of ^{131}I absorbed in the body in Bq s.

(d) (2 points) Which type of radiation (beta or gamma) is most suited for treating the Graves' disease? Justify your answer on physical grounds.

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7. Detection of radiation

The detection of gamma photons requires the conversion of the neutral photon into an electronic charge. Below 1 MeV, there are two reactions that accomplish this: the photoelectric effect and Compton scattering. Consider the 662 keV photons of a ^{137}Cs source incident on a NaI(Tl) detector:

(a) (2 points) Determine the energy of the electron emerging from photoelectric absorption in the detector.

(b) (1 point) What is the maximum energy of a Compton-scattered electron in the detector?

(c) (2 points) What is the minimum energy of a Compton-scattered electron in the detector?

(d) (2 points) Using the above results, sketch the shape of the pulse-height distribution a NaI(Tl) detector would produce.

(e) (3 points) The mass attenuation coefficient of 662 keV photons is about 0.0079 cm^2/g in NaI, which has a density of 3,700 kg/m^3. One million 622 keV photons travel along the axis of a 25 mm-long NaI(Tl) crystal. How many of them will be detected?

END OF EXAMINATION
