National Examination,
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.
4. This exam has 7 questions, for a total of 100 points.
5. Worth of each question, or part of, is given for each question.
6. You are required to answer only eighty (80) points worth of questions or parts of. That is, the full mark is **80** points.
7. Duration: Three (3) hours

1. (a) (6 points) Calculate the binding energy per nucleon for the following nuclides:
   (i) ${}^{2}_{1}$H (2.0141018),
   (ii) ${}^{41}_{20}$Ca (40.9622783),
   (iii) ${}^{238}_{92}$U (238.0507826).

   The numbers in parenthesis are the atomic masses. The proton's mass is $m_p = 1.00727647$ u, and the neutron's mass is $m_n = 1.008665012$ u; where u $= 931.4943$ MeV.

   (b) (6 points) Based on your calculations, explain why:
   (i) Deuterium burning is possible (deuterium burning occurs in stars and some substellar objects when a deuterium nucleus and a proton combine to form a helium-3 nucleus).
   (ii) ${}^{238}_{92}$U is a fertile material for fission.
   (iii) ${}^{41}_{20}$Ca is neither suited for fission nor fusion.

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2. The Poisson distribution of a variable x in a population of n entities has the normalized form:

$$P(n, x) = \frac{(x)^n \exp(-x)}{n!}$$

   (a) (3 points) The Poisson distribution is suited to describing the decay of radionuclides. Explain why?

   (b) (4 points) Show that the activity λt is equal to the expected (mean) number of decays within a time interval t for a radionuclide of a time constant λ. Hint: Use $x = \lambda t$ in the Poisson distribution, and recognize that: $\sum_{n=0}^{\infty} n x^n \exp(-x)/n! = x$.

   (c) (4 points) What is the probability of a nucleus surviving a time t then decaying within $t + \Delta t$?

   (d) (4 points) What is the mean life-time of a radionuclide that has a decay constant λ?

   (e) (3 points) Can equilibrium conditions be reached when a parent nuclide decays to a daughter of about the same half-life? Mathematically validate your answer.

3. ^{241}Am (a gamma-ray source which emits gamma-rays of about 60 keV in energy) is often used to assess the adequacy of the concrete shielding of rooms housing x-ray machines. The following data may help you in answering the following questions.

   - Mass attenuation coefficient for 60 keV photons is estimated to be 0.17 cm^2/g.
   - Tenth-value layer (TVL) of concrete is 21.5 mm for 60 kV x-rays.
   - Concrete density is 2,300 kg/m^3.

   (a) (2 points) Schematically sketch the energy spectrum of the photons emitted from the x-ray machine, and explain its behavior.

   (b) (2 points) Determine the TVL for ^{241}Am photons in concrete.

   (c) (2 points) Compare the TVL value for the 60 keV ^{241}Am photons to that of the 60 kV x-rays, and provide the physical basis for their difference.

   (d) (5 points) Calculate and tabulate the expected relative reduction in intensity for both the above x-rays and gamma-rays when made normally incident on concrete slabs of thicknesses of 25 mm, 50 mm and 100 mm, respectively. State the assumptions made in your calculations.

   (e) (3 points) Which of the above two radiation types, and what of the above three thicknesses, would more likely result in radiation dose buildup?

   (f) (3 points) Based on the results of the above calculations, assess the adequacy of using this isotopic source to determine whether the radiation intensity can be reduced to practically zero outside a room surrounded with a 50 mm concrete shield.

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4. (a) Moisture content in a material may be measured using neutrons:

   (i) (3 points) Explain the physical basis behind a moisture probe that employs an isotopic neutron source.

   (ii) (7 points) For a neutron moisture gauge based on the principle you described above:
   - Suggest a suitable neutron source.
   - Suggest a suitable neutron detector.
   - Sketch a geometric configuration showing the location of the source and the detector versus each other and versus the test material for which the moisture content is to be determined.

   (b) (2 points) Moisture content in a material may be measured using microwaves (at certain frequencies), explain the physical basis behind a moisture probe that employs a microwave generator.

   (c) (6 points) Fast neutrons, microwave radiation, and gamma rays are neutral forms of radiation. For each type of radiation, propose one method for producing charged particles that facilitate their detection.

5. 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 16 g.

   (a) (1 point) Why iodine in particular is 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-eighth ($\frac{1}{8}$) 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) Estimate the absorbed fraction of ^{131}I gamma in the thyroid, using the data provided in the table below:

   Absorbed fraction of a gamma emitter uniformly distributed in the thyroid **per gram**

Photon Energy	Absorbed Fraction
100 keV	1.44×10^{-3}
200 keV	1.55×10^{-3}
500 kev	1.66×10^{-3}

   (e) (4 points) Calculate the absorbed gamma cumulative dose to the thyroid from this treatment.

   (f) (4 points) Calculate the absorbed beta cumulative dose to the thyroid from this treatment.

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

6. (10 points) The mayor of a small town that has an abandoned uranium mine has expressed concerns to regulating authorities about the perceived high radiation level in the town. As an employee of this regulating authority, your supervisor has asked you to prepare a radiation survey plan, identifying what needs to be monitored and how. Present this plan in the form of a one-page memorandum to your supervisor.

7. (a) (2 points) The maximum allowed total effective dose assigned by a nuclear facility to a temporary, but trained, nuclear energy worker (NEW), was 10 mSv, during the six-month duration of the contract of employment. Is this within regulatory limits?

   (b) (5 points) After three (3) months of employment, the above worker's external dose was found to be 2.5 mSv. In addition, radiation work permits and air sampling showed that this worker was also exposed to the following airborne radioactivity:

Radionuclide	Total Exposure Time	Concentration (kBq/m^3)	DAC* (kBq/m^3)
^{125}I	2 weeks	0.4	1.2
^{131}I	2 weeks	0.4	0.8
^{89}Sr	1 week	8	16
^{90}Sr	1 week	0.08	0.32

*DAC= derived air concentration = concentration of a given radionuclide in air which, if breathed by the reference person for a working year of 2,000 hours under conditions of light work (with an inhalation rate of 1.2 m^3 of air per hour), results in an intake of one annual limit on intake.

Determine whether the total effective dose is within the prescribed limits. Should the worker be assigned to work that does not involve exposure to radiation in the remaining three months of the employment contract?

END OF EXAMINATION

Marking Scheme

Q.1: 12 points: (a) 6 points, (b) 6 points.

Q.2: 15 points: 3 points for each part.

Q.3: 15 points: (a) 2 points, (b) 2 points, (c) 2 points, (d) 5 points, (e) 3 points, (f) 3 points.

Q.4: 18 points: (a) 10 points, (b) 2 points, (c) 6 points.

Q.5: 18 points: (a) 1 point, (b) 3 points (c) 2 points, (d) 2 points, (e) 4 points, (f) 4 points, (g) 2 points.

Q.6: 10 points,

Q.7: 7 points: (a) 2 points, (b) 5 points.