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Department of Physics

Examination paper for TFY4225 Nuclear and Radiation Physics

Examination date: 1 Dec 2022

Examination time (from-to): 15:00-19:00

Permitted examination support material: Calculator, pen

Academic contact during examination: Johanna Vannesjö
Phone: 46749776

Academic contact present at the exam location: Yes (16:00-17:00)

OTHER INFORMATION

Get an overview of the question set before you start answering the questions.

Read the questions carefully and make your own assumptions. If a question is unclear/vague, make your own assumptions and specify them in your answer. Only contact academic contact in case of errors or insufficiencies in the question set. Address an invigilator if you wish to contact the academic contact. Write down the question in advance.

InsperaScan: For some questions you may answer on handwritten sheets. Other questions must be answered directly in Inspera. At the bottom of the question you will find a seven-digit code. Fill in this code in the top left corner of the sheets you wish to submit. We recommend that you do this during the exam. If you require access to the codes after the examination time ends, click “Show submission”.

Multiple choice questions: The exam includes a few multiple choice questions. These need to be answered in Inspera.

Weighting: The maximum achievable score for the exam is 100. The maximum score for each question is given in brackets after each question.

Notifications: If there is a need to send a message to the candidates during the exam (e.g. if there is an error in the question set), this will be done by sending a notification in Inspera. A dialogue box will appear. You can re-read the notification by clicking the bell icon in the top right-hand corner of the screen.

Withdrawing from the exam: If you become ill or wish to submit a blank test/withdraw from the exam for another reason, go to the menu in the top right-hand corner and click “Submit blank”. This cannot be undone, even if the test is still open.

Access to your answers: After the exam, you can find your answers in the archive in Inspera. Be aware that it may take a working day until any hand-written material is available in the archive.

Language: All questions are given in English, but you may answer in either English or Norwegian.

i Constants and formulas

Physical constants

Speed of light	c	$2.99792458 \times 10^{8} m/s$
Charge of electron	e	$1.602189 \times 10^{-19} C$
Boltzmann constant	k_B	$1.38066 \times 10^{-23} J/K$
		$8.6174 \times 10^{-5} eV/K$
Planck's constant	h	$6.62618 \times 10^{-34} J{\cdot}s$
		$4.13570 \times 10^{-15} eV{\cdot}s$
	$\hbar = h/2\pi$	$1.054589 \times 10^{-34} J{\cdot}s$
		$6.58217 \times 10^{-16} eV{\cdot}s$
	hc	$1239.853\ MeV{\cdot}fm$
	$\hbar c$	$197.329\ MeV{\cdot}fm$
Avogadro's number	N_A	$6.022045 \times 10^{23} mole^{-1}$
Coulomb constant	$e^2/4\pi\epsilon_0$	$1.439976\ MeV{\cdot}fm$

Conversion factors

$1\ eV = 1.602189 \times 10^{-19} J$
$1\ b = 10^{-28} m^2$

Formulas

Coulomb force:
$|F| = \frac{|q_1 q_2|}{4\pi\epsilon_0 r^2}$
Coulomb potential:
$P = \frac{q_1 q_2}{4\pi\epsilon_0 r}$

SEMF:
$M(Z,A) = Zm(^1H) + Nm_n - B(Z,A)/c^2$
$B(Z,A) = a_V A - a_s A^{2/3} - a_C Z(Z-1)A^{-1/3} - a_{sym}\frac{(A-2Z)^2}{A} + \delta$
$a_V = 15.5\ MeV,\ a_s = 16.8\ MeV,\ a_C = 0.72\ MeV,\ a_{sym} = 23\ MeV,\ \delta = \pm 34 \cdot A^{-3/4}\ MeV$

Nuclear decay:
$Q = (\sum m_{initial} - \sum m_{final})c^2$
$N(t) = N_0 e^{-\lambda t}$
$A(t) \equiv \lambda N(t) = A_0 e^{-\lambda t}$
$A_2 = A_0 \frac{\lambda_2}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})$

Semi-classical theory of α decay:
$\lambda = fP$
$f = \frac{v}{a}$
$P = e^{-2G}$
$G = \sqrt{\frac{2m}{\hbar^2 Q}}\frac{zZ'e^2}{4\pi\epsilon_0}[cos^{-1}\sqrt{x} - \sqrt{x(1-x)}]$
$x = a/b = Q/B$

Internal dosimetry:

$D = \sum_T w_T \sum_R w_R D_R(r_T, T_D)$
$D_R(r_T, T_D) = \sum_{r_S} \tilde{A}(r_S, T_D) S(r_T \leftarrow r_S)$
$S(r_T \leftarrow r_S) = \frac{1}{M(r_T)} \sum_i E_i Y_i \phi(r_T \leftarrow r_S, E_i)$
$\tilde{A}(r_S, T_D) = \int_0^{T_D} A(r_S, t) dt$

Rest masses

$1\ u = 931.502\ MeV/c^2 = 1.660566 \times 10^{-27} kg$
$m_e = 511\ keV/c^2$
$\Delta_n = 8071\ keV$
$\Delta^1 H = 7289\ keV$
$\Delta^2 H = 13136\ keV$
$\Delta^3 He = 14931\ keV$
$\Delta^4 He = 2425\ keV$
$\Delta^{13} C = 3125\ keV$
$\Delta^{13} N = 5346\ keV$
$\Delta^{74} Ge = -73422\ keV$
$\Delta^{74} Se = -72213\ keV$
$\Delta^{126} Sn = -86015\ keV$
$\Delta^{126} Sb = -86390\ keV$
$\Delta^{126} Te = -90064\ keV$

Source mass excesses: https://www.nndc.bnl.gov/nudat3/

Radiation weighting factors

Type of radiation	Energy range	w_R
Photons, electrons	All energies	1
Neutrons	< 10 keV	5
	10 - 100 keV	10
	0.1 - 2 MeV	20
	2 - 20 MeV	10
	> 20 MeV	5
Protons	< 20 MeV	5
Alpha particles, heavy nuclei		20

Source: Lilley, Chapter 7

Tissue	w_T
Remaining tissues (any not listed below)	0.12
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Gonads	0.08
Liver	0.04
Oesophagus	0.04
Thyroid	0.04
Bladder	0.04
Bone surface	0.01

Tissue	w_T
Brain	0.01
Salivary glands	0.01
Skin	0.01
TOTAL	**1.00**

Source: ICRP 103 (ICRP 2007)

Periodic table

See pdf (left-hand side)

Source: https://commons.wikimedia.org/w/index.php?curid=98955505

1 Question 1

One of the long-living nuclides present in high-level nuclear waste is ^{126}Sn. ^{126}Sn decays with a half-life of $0.218 \cdot 10^6$ years to ^{126}Sb. ^{126}Sb in turn decays with a half-life of 12.35 days to ^{126}Te, which is stable.

a. How long does it take for ^{126}Sn to decay to 1% of its starting activity? (4p)
b. Based on the formula for the activity of the daughter nuclei in a chain of radioactive decays, derive a simplified expression of the activity of the daughter for the case when the half-life of the daughter is much shorter than the half-life of the parent nucleus. (4p)
c. Assume you have a sample with activity A_0 of ^{126}Sn, and without any of the daughter nucleus, ^{126}Sb, at $t = 0$. How long does it take for ^{126}Sb to reach 99% of its activity in secular equilibrium? (4p)

Fill in your answer here

Format

Words: 0

Maximum marks: 12

2 Question 2

Detectors

a. Describe the principles of a Geiger-Müller detector (6p)
b. How does a fast neutron detector work? (6p)

Fill in your answer here

Words: 0

Maximum marks: 12

3 Question 3

The semi-empirical mass formula (SEMF) is a formula to estimate the mass of nuclides.

a. Based on the SEMF, derive an equation to find the most stable nuclide for constant A (isobars) (8p)
b. Which terms for the binding energy in the SEMF are relevant to determine the most stable isobar (i.e. contribute to the equation derived in a))? Please explain the physical meaning of those terms. (8p)
c. Estimate the most stable nuclide for isobars with A = 121 and A = 74. (4p)
d. Isobars with A=74 contain two stable nuclides: ^{74}Ge and ^{74}Se. How does this compare with your results in c)? Explain any deviations. (4p)

Fill in your answer here

Format | B I U x_2 x^2 | I_x | | Ω | Σ |

Words: 0

Maximum marks: 24

4 Question 4

The idea of a fusion reactor is to let two light nuclei combine into one heavier nucleus and to release energy in the process. One of the potential reactions that could be used in a fusion reactor is $^2H + ^3He \rightarrow ^4He\ + ^1H$. However, fusion is generally prevented from happening because of the repulsion between the positively charged nuclei due to the Coulomb force. That is why fusion is more likely to happen at very high temperatures, where the particles have high kinetic energy. The most probable kinetic energy, T_p, of a particle at a given temperature can be estimated by the Boltzmann distribution, yielding: $T_p = k_B \cdot T$, where T is the temperature and k_B is the Boltzmann constant.

a. Calculate the height of the Coulomb barrier between ^{2}H and ^{3}He. Assume $R = R_0 \cdot A^{1/3}$, where $R_0 = 1.4\ fm$. (4p)
b. What temperature is required for the particles to overcome the Coulomb barrier classically? (2p)

Particles with lower kinetic energy than the Coulomb barrier still have a probability to fuse due to tunnelling. Assume a temperature of 10^8 K.

c. How close can the particles get to each other in the classical case? (4p)
d. Estimate the probability of tunnelling happening in the case of a head-on collision between ^{2}H and ^{3}He at this temperature. Use the semi-classical theory derived for α decay. (10p)

Fill in your answer here

Maximum marks: 20

5 Question 5

^{13}N can be used for PET (Positron Emission Tomography) imaging to estimate perfusion through the myocardium. ^{13}N decays via 100% β^+ decay to the ground state of ^{13}C with a half-life of 10 min. Assume that an initial activity of 600 MBq is injected into a patient before a PET exam, and that there is no biological clearance.

a. Calculate the Q-value of the decay of ^{13}N (4p)
b. Estimate the effective dose to the patient if the radionuclide distributes uniformly in the body. (12p)
c. Estimate the effective dose if 20% of the radionuclide accumulates in the liver (1500g), 20% in the bladder (40g), and 20% in the brain (1300g), with the rest uniformly distributed in the body. (6p)

Fill in your answer here

Format

Words: 0

Maximum marks: 22

6 MCQ1

Which of the following statements is **false**
Select one alternative:

- The energy levels in the nuclear shell model are equal to the energy levels of electrons in the atomic model
- Spin-orbit coupling is an important feature of the shell model
- Levels in the shell model fill up with neutrons and protons independently
- The shell model can be used to explain the magic numbers
- The shell model can be used to estimate spin-parity of nuclei

Maximum marks: 2

7 MCQ2

Which of the following statements is **true**
Select one alternative:

- Gamma decay changes the nuclear species
- Negative beta decay generally occurs in proton-rich nuclei
- Gamma decay usually has long half-lives
- Alpha or beta decay is often followed by gamma decay
- Alpha decay predominantly happens in light nuclei

Maximum marks: 2

8 MCQ3

Which of the following statements is **true**
Select one alternative:

- Heavy charged particles deposit their kinetic energy through many interactions with electrons in materia
- Heavy charged particles penetrate deeper into materia than light charged particles of the same kinetic energy
- The energy deposition through photon interaction with materia has a Bragg peak
- Neutrons slow down by interacting with electrons and nuclei in materia
- Electrons follow a straight path in interaction with materia

Maximum marks: 2

9 MCQ4

Which of the following statements is **false**
Select one alternative:

- Most of the DNA damage due to ionizing radiation is indirect via free radicals
- Alpha radiation is high LET radiation
- DNA damage is the main mechanism through which ionizing radiation kills cells
- Cells are less sensitive to ionizing radiation in a high-oxygen environment
- High LET (linear energy transfer) is more damaging to biological tissue than low LET

Maximum marks: 2

10 MCQ5

Which of the following statements is **true**
Select one alternative:

- A monoenergetic beam of a given beam intensity delivers the same dose to all types of materia
- KERMA is a measure of energy transferred for photon and electron beams
- Only photon interactions contribute to the absorbed dose
- In the charged particle equilibrium (CPE) the collision KERMA directly corresponds to the dose for a photon beam
- Fluence and energy fluence are the same

Maximum marks: 2

Document 2
Attached

Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		