BINDURA UNIVERSITY OF SCIENCE EDUCATION

Faculty of Science and Engineering

Department of Engineering and Physics

BACHELOR OF SCIENCE EDUCATION HONOURS DEGREE

Physics

AUG 2024

PH309

Nuclear Physics

Duration: Three (3) Hours

Answer ALL parts of Section A and any THREE questions from Section B. Section A carries 40 marks and each question of Section B carries 20 marks.

Clearly show ALL working

You may not start to read the questions printed on the subsequent pages until instructed to do so by the Invigilator.

Table 44.2 Chemical and Nuclear Information for Selected Isotopes

Atomic Number Z	Element	Chemical Symbol	Mass Number A (* means radioactive)	Mass of Neutral Atom (u)	Percent Abundance	Half-life, if Radioactive $T_{1/2}$
−1	electron	e^-	0	0.000 549		
0	neutron	n	1*	1.008 665		614 s
1	hydrogen	^{1}H = p	1	1.007 825	99.988 5	
	[deuterium	^{2}H = D]	2	2.014 102	0.011 5	
	[tritium	^{3}H = T]	3*	3.016 049		12.33 yr
2	helium	He	3	3.016 029	0.000 137	
	[alpha particle	α = ^{4}He]	4	4.002 603	99.999 863	
			6*	6.018 889		0.81 s
3	lithium	Li	6	6.015 123	7.5	
			7	7.016 005	92.5	
4	beryllium	Be	7*	7.016 930		53.3 d
			8*	8.005 305		10^{-17} s
			9	9.012 182	100	
5	boron	B	10	10.012 937	19.9	
			11	11.009 305	80.1	
6	carbon	C	11*	11.011 434		20.4 min
			12	12.000 000	98.93	
			13	13.003 355	1.07	
			14*	14.003 242		5 730 yr
7	nitrogen	N	13*	13.005 739		9.96 min
			14	14.003 074	99.632	
			15	15.000 109	0.368	
8	oxygen	O	14*	14.008 596		70.6 s
			15*	15.003 066		122 s
			16	15.994 915	99.757	
			17	16.999 132	0.038	
			18	17.999 161	0.205	
9	fluorine	F	18*	18.000 938		109.8 min
			19	18.998 403	100	
10	neon	Ne	20	19.992 440	90.48	
11	sodium	Na	23	22.989 769	100	
12	magnesium	Mg	23*	22.994 124		11.3 s
			24	23.985 042	78.99	
13	aluminum	Al	27	26.981 539	100	
14	silicon	Si	27*	26.986 705		4.2 s
15	phosphorus	P	30*	29.978 314		2.50 min
			31	30.973 762	100	
			32*	31.973 907		14.26 d
16	sulfur	S	32	31.972 071	94.93	
19	potassium	K	39	38.963 707	93.258 1	
			40*	39.963 998	0.011 7	1.28 × 10^{9} yr
20	calcium	Ca	40	39.962 591	96.941	
			42	41.958 618	0.647	
			43	42.958 767	0.135	
25	manganese	Mn	55	54.938 045	100	
26	iron	Fe	56	55.934 938	91.754	
			57	56.935 394	2.119	

continued

Table 44.2 Chemical and Nuclear Information for Selected Isotopes *(continued)*

Atomic Number Z	Element	Chemical Symbol	Mass Number A (* means radioactive)	Mass of Neutral Atom (u)	Percent Abundance	Half-life, if Radioactive $T_{1/2}$
27	cobalt	Co	57*	56.936 291		272 d
			59	58.933 195	100	
			60*	59.933 817		5.27 yr
28	nickel	Ni	58	57.935 343	68.076 9	
			60	59.930 786	26.223 1	
29	copper	Cu	63	62.929 598	69.17	
			64*	63.929 764		12.7 h
			65	64.927 789	30.83	
30	zinc	Zn	64	63.929 142	48.63	
37	rubidium	Rb	87*	86.909 181	27.83	
38	strontium	Sr	87	86.908 877	7.00	
			88	87.905 612	82.58	
			90*	89.907 738		29.1 yr
41	niobium	Nb	93	92.906 378	100	
42	molybdenum	Mo	94	93.905 088	9.25	
44	ruthenium	Ru	98	97.905 287	1.87	
54	xenon	Xe	136*	135.907 219		2.4 × 10^{21} yr
55	cesium	Cs	137*	136.907 090		30 yr
56	barium	Ba	137	136.905 827	11.232	
58	cerium	Ce	140	139.905 439	88.450	
59	praseodymium	Pr	141	140.907 653	100	
60	neodymium	Nd	144*	143.910 087	23.8	2.3 × 10^{15} yr
61	promethium	Pm	145*	144.912 749		17.7 yr
79	gold	Au	197	196.966 569	100	
80	mercury	Hg	198	197.966 769	9.97	
			202	201.970 643	29.86	
82	lead	Pb	206	205.974 465	24.1	
			207	206.975 897	22.1	
			208	207.976 652	52.4	
			214*	213.999 805		26.8 min
83	bismuth	Bi	209	208.980 399	100	
84	polonium	Po	210*	209.982 874		138.38 d
			216*	216.001 915		0.145 s
			218*	218.008 973		3.10 min
86	radon	Rn	220*	220.011 394		55.6 s
			222*	222.017 578		3.823 d
88	radium	Ra	226*	226.025 410		1 600 yr
90	thorium	Th	232*	232.038 055	100	1.40 × 10^{10} yr
			234*	234.043 601		24.1 d
92	uranium	U	234*	234.040 952		2.45 × 10^5 yr
			235*	235.043 930	0.720 0	7.04 × 10^8 yr
			236*	236.045 568		2.34 × 10^7 yr
			238*	238.050 788	99.274 5	4.47 × 10^9 yr
93	neptunium	Np	236*	236.046 570		1.15 × 10^5 yr
			237*	237.048 173		2.14 × 10^6 yr
94	plutonium	Pu	239*	239.052 163		24 120 yr

Source: G. Audi, A. H. Wapstra, and C. Thibault, "The AME2003 Atomic Mass Evaluation," *Nuclear Physics A* 729:337–676, 2003.

APPENDIX C

Periodic Table of the Elements

Symbol — Ca 20 — Atomic number
Atomic mass† — 40.078
$4s^2$ — Electron configuration

Group I	Group II	Transition elements						
H 1 1.0079 $1s$								
Li 3 6.941 $2s^1$	Be 4 9.0122 $2s^2$							
Na 11 22.990 $3s^1$	Mg 12 24.305 $3s^2$							
K 19 39.098 $4s^1$	Ca 20 40.078 $4s^2$	Sc 21 44.956 $3d^1 4s^2$	Ti 22 47.867 $3d^2 4s^2$	V 23 50.942 $3d^3 4s^2$	Cr 24 51.996 $3d^5 4s^1$	Mn 25 54.938 $3d^5 4s^2$	Fe 26 55.845 $3d^6 4s^2$	Co 27 58.933 $3d^7 4s^2$
Rb 37 85.468 $5s^1$	Sr 38 87.62 $5s^2$	Y 39 88.906 $4d^1 5s^2$	Zr 40 91.224 $4d^2 5s^2$	Nb 41 92.906 $4d^4 5s^1$	Mo 42 95.94 $4d^5 5s^1$	Tc 43 (98) $4d^5 5s^2$	Ru 44 101.07 $4d^7 5s^1$	Rh 45 102.91 $4d^8 5s^1$
Cs 55 132.91 $6s^1$	Ba 56 137.33 $6s^2$	57–71*	Hf 72 178.49 $5d^2 6s^2$	Ta 73 180.95 $5d^3 6s^2$	W 74 183.84 $5d^4 6s^2$	Re 75 186.21 $5d^5 6s^2$	Os 76 190.23 $5d^6 6s^2$	Ir 77 192.2 $5d^7 6s^2$
Fr 87 (223) $7s^1$	Ra 88 (226) $7s^2$	89–103**	Rf 104 (261) $6d^2 7s^2$	Db 105 (262) $6d^3 7s^2$	Sg 106 (266)	Bh 107 (264)	Hs 108 (277)	Mt 109 (268)

*Lanthanide series	La 57 138.91 $5d^1 6s^2$	Ce 58 140.12 $5d^1 4f^1 6s^2$	Pr 59 140.91 $4f^3 6s^2$	Nd 60 144.24 $4f^4 6s^2$	Pm 61 (145) $4f^5 6s^2$	Sm 62 150.36 $4f^6 6s^2$
**Actinide series	Ac 89 (227) $6d^1 7s^2$	Th 90 232.04 $6d^2 7s^2$	Pa 91 231.04 $5f^2 6d^1 7s^2$	U 92 238.03 $5f^3 6d^1 7s^2$	Np 93 (237) $5f^4 6d^1 7s^2$	Pu 94 (244) $5f^6 7s^2$

Note: Atomic mass values given are averaged over isotopes in the percentages in which they exist in nature.

† For an unstable element, mass number of the most stable known isotope is given in parentheses.

			Group III	Group IV	Group V	Group VI	Group VII	Group 0
							H 1 1.007 9 $1s^1$	He 2 4.002 6 $1s^2$
			B 5 10.811 $2p^1$	C 6 12.011 $2p^2$	N 7 14.007 $2p^3$	O 8 15.999 $2p^4$	F 9 18.998 $2p^5$	Ne 10 20.180 $2p^6$
			Al 13 26.982 $3p^1$	Si 14 28.086 $3p^2$	P 15 30.974 $3p^3$	S 16 32.066 $3p^4$	Cl 17 35.453 $3p^5$	Ar 18 39.948 $3p^6$
Ni 28 58.693 $3d^8 4s^2$	Cu 29 63.546 $3d^{10} 4s^1$	Zn 30 65.41 $3d^{10} 4s^2$	Ga 31 69.723 $4p^1$	Ge 32 72.64 $4p^2$	As 33 74.922 $4p^3$	Se 34 78.96 $4p^4$	Br 35 79.904 $4p^5$	Kr 36 83.80 $4p^6$
Pd 46 106.42 $4d^{10}$	Ag 47 107.87 $4d^{10} 5s^1$	Cd 48 112.41 $4d^{10} 5s^2$	In 49 114.82 $5p^1$	Sn 50 118.71 $5p^2$	Sb 51 121.76 $5p^3$	Te 52 127.60 $5p^4$	I 53 126.90 $5p^5$	Xe 54 131.29 $5p^6$
Pt 78 195.08 $5d^9 6s^1$	Au 79 196.97 $5d^{10} 6s^1$	Hg 80 200.59 $5d^{10} 6s^2$	Tl 81 204.38 $6p^1$	Pb 82 207.2 $6p^2$	Bi 83 208.98 $6p^3$	Po 84 (209) $6p^4$	At 85 (210) $6p^5$	Rn 86 (222) $6p^6$
Ds 110 (271)	Rg 111 (272)	Cn 112 (285)	113†† (284)	Fl 114 (289)	115†† (288)	Lv 116 (293)	117†† (294)	118†† (294)

Eu 63 151.96 $4f^7 6s^2$	Gd 64 157.25 $4f^7 5d^1 6s^2$	Tb 65 158.93 $4f^8 5d^1 6s^2$	Dy 66 162.50 $4f^{10} 6s^2$	Ho 67 164.93 $4f^{11} 6s^2$	Er 68 167.26 $4f^{12} 6s^2$	Tm 69 168.93 $4f^{13} 6s^2$	Yb 70 173.04 $4f^{14} 6s^2$	Lu 71 174.97 $4f^{14} 5d^1 6s^2$
Am 95 (243) $5f^7 7s^2$	Cm 96 (247) $5f^7 6d^1 7s^2$	Bk 97 (247) $5f^8 6d^1 7s^2$	Cf 98 (251) $5f^{10} 7s^2$	Es 99 (252) $5f^{11} 7s^2$	Fm 100 (257) $5f^{12} 7s^2$	Md 101 (258) $5f^{13} 7s^2$	No 102 (259) $5f^{14} 7s^2$	Lr 103 (262) $5f^{14} 6d^1 7s^2$

†† Elements 113, 115, 117, and 118 have not yet been officially named. Only small numbers of atoms of these elements have been observed.

Note: For a description of the atomic data, visit *physics.nist.gov/PhysRefData/Elements/per_text.html*.

$$r = aA^{1/3}; \quad a = 1.2 \times 10^{-15} m$$

$$1\,amu = 931.494\,3 \frac{MeV}{c^2} \quad ; \quad 1\,MeV = 1.60 \times 10^{-13}\,J; \quad 1\,kWh = 3.6 \times 10^6\,J$$

$$V = k_e \frac{q_1 q_2}{r}; \qquad k_e = 8.99 \times 10^9\,N \cdot m^2/C^2$$

$$1\,Ci = 3.7 \times 10^{10}\,decays/s \quad ; \quad 1\,Bq = 1\,decay/s$$

$$N_A = 6.02 \times 10^{23}\,\,atoms/mol \quad ; \quad 1.38 \times 10^{-23}\,J/K$$

Section A

1. (a) Determine the mass number of a nucleus whose radius is approximately equal to two-thirds the radius of ${}^{230}_{88}Ra$. Identify the element. Are any other answers possible? Explain.

[6]

(b) If a nucleus such as radium-226 initially at rest undergoes alpha decay, which has more kinetic energy after the decay, the alpha particle or the daughter nucleus? Explain your answer.

[4]

(c) Explain why water is a better shield against neutrons than lead or steel.

[4]

(d) Define the reproduction constant, K, used in the context of nuclear reactors. Describe the nuclear reactor when $K = 1, K < 1$ and $K > 1$.

[4]

(e) Give a brief account of the three layers of radiation containment in a nuclear reactor.

[6]

(f) Explain what is meant by the term mirror isobars. Find the difference in binding energy for the two mirror isobars ${}^{15}_{8}O$ and ${}^{15}_{7}N$.

[4]

(g) A sample of the isotope iodine -131, which has a half-life of 8.04 days, has an activity of 5.0 mCi at the time of shipment. Upon receipt of the sample at a medical laboratory, the activity is 2.1 mCi. How much time has elapsed between the two measurements?

[4]

(h) For the nuclear force to overcome the repulsive Coulomb force, the separation distance between two deuterons must be approximately $1.0 \times 10^{-14}\ m$.

(i) Calculate the height of the potential barrier due to the repulsive force.

[3]

(ii) Estimate the temperature required for a deuteron to overcome the potential barrier, assuming an energy of $3k_BT/2$ per deuteron.

[2]

(iii) Find the energy released in the D–D reaction: $d + d \longrightarrow t + p$

[3]

Section B

2.(a) The binding energy of a nucleus with atomic number Z and mass number A can be expressed by the semiempirical binding-energy formula

$$E_b = C_1 A - C_2 A^{2/3} - C_3 \frac{Z(Z-1)}{A^{1/3}} - C_4 \frac{(N-Z)^2}{A}$$

where values for the constants C_1, C_2, C_3 and C_4 are respectively 15.7, 17.8, 0.71 and 23.6 MeV for nuclei having A≥15.

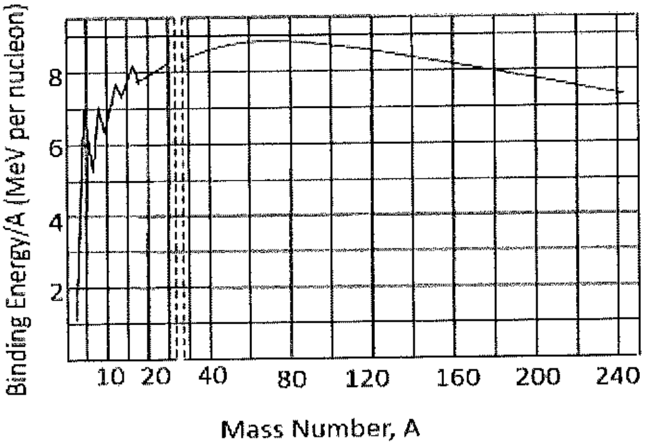
(i) For the alpha particle decay ${}^{230}_{90}Th \longrightarrow {}^{226}_{88}Ra + {}^{4}_{2}He$ use this binding-energy formula to generate theoretical estimates of the binding energy for the two heavy nuclei involved in this process. Given that the total binding energy of the alpha particle is 28.3MeV, find the energy Q released in the decay.

[6]

(ii) This energy appears as the kinetic energy of the products of the decay. If the original thorium nucleus was at rest, use conservation of momentum and conservation of energy to find the kinetic energy of the daughter nucleus radium-226. Comment on the result you get.

[6]

(b) The following plot shows the average binding energy per nucleon for stable nuclei as a function of mass number.



(i) Use this plot to estimate the mass of ${}^{235}_{92}U$ in atomic mass units.

[5]

(ii) Estimate the energy released when a nucleus of ${}^{235}_{92}U$ undergoes fission into the fragments ${}^{87}_{35}Br$ and ${}^{145}_{57}La$ with the release of three neutrons.

[3]

3. Consider the two nuclear reactions

$$A + B \longrightarrow C + E$$

$$C + D \longrightarrow F + G$$

(a) Show that the net disintegration energy for these two reactions

$$Q_{net} = Q_I + Q_{II}$$

is identical to the disintegration energy for the net reaction

$$A + B + D \longrightarrow E + F + G$$

[6]

(b) One chain of reactions in the proton–proton cycle in the Sun's core is

$$p + p \longrightarrow d + e^+ + \nu$$

$$e^+ + e^- \longrightarrow 2\gamma$$

$$p + d \longrightarrow {}^3_2He + \gamma$$

$$p + t \longrightarrow {}^4_2He + e^+ + \nu$$

$$e^+ + e^- \longrightarrow 2\gamma$$

Based on part (a), what is Q_{net} for this sequence?

[6]

(c) Given that the Sun radiates energy at the rate of $3.85 \times 10^{26}\ W$ calculate the number of protons fused per second.

[5]

(d) Explain why the proton–proton interaction is not suitable for use in a fusion reactor.

[3]

4. (a) Give the similarities and differences between fusion and fission.

[4]

(b) Discuss the advantages and disadvantages of fission reactors from the point of view of safety, pollution, and resources. Make a comparison with power generated from the burning of fossil fuels.

[6]

(c) An all-electric home uses approximately 2 000 kWh of electric energy per month.

(i) How much uranium-235 would be required to provide this house with its energy needs for one year? Assume 100 % conversion efficiency and 208 MeV released per fission.

[6]

(ii) Assuming all energy released from fusion could be captured, how many fusion events described by the reaction

$$d + t \longrightarrow {}^{4}_{2}He + n \qquad Q = 17.59\ MeV$$

would be required to keep the home running for one year?

[4]

5. (a) Give two factors that make a terrestrial fusion reaction difficult to achieve.

[2]

(b) Lawson's criterion states that the product of ion density and confinement time must exceed a certain number before a break-even fusion reaction can occur. Why should these two parameters determine the outcome?

[4]

(c) Find the rms speed of deuterons in a plasma at a temperature of $4.00\ \times 10^{8}\ K$. Hence estimate the order of magnitude of the time interval during which such a plasma would remain in a 10.0-cm cube if no steps were taken to contain it. [Assume $m_d \approx 2m_p$].

[4]

(d) When a star has exhausted its hydrogen fuel, it may fuse other nuclear fuels. At temperatures above $1.00 \times 10^{8}\ K$, helium fusion can occur. Consider the following processes.

(i) Two alpha particles fuse to produce a nucleus A and a gamma ray. What is nucleus A?

[2]

(ii) Nucleus A from part (i) absorbs an alpha particle to produce nucleus B and a gamma ray. What is nucleus B?

[2]

(iii) Find the total energy released in the sequence of reactions given in parts (i) and (ii).

[6]

6. (a) Explain the terms somatic damage and genetic damage used in reference reference to damage caused by radiation in biological systems.

[4]

(b) Give a brief description of brachytherapy.

[4]

(c) A sealed capsule containing the radiopharmaceutical phosphorus-32, an e^-emitter, is implanted into a patient's tumor. The average kinetic energy of the beta particles is 700 keV. The initial activity is 5.22 MBq. Assume the beta particles are completely absorbed in 100 g of tissue. Determine the absorbed dose during a 10.0-day period.

[One rad is that amount of radiation that increases the energy of 1 kg of absorbing material by $1 \times 10^{-2}\ J$.]

[6]

(d) A small building has become accidentally contaminated with radioactivity. The longest-lived material in the building is strontium-90. (It is particularly dangerous because it substitutes for calcium in bones.) Assume the building initially contained 5.00 kg of this substance uniformly distributed throughout the building and the safe level is defined as less than 10.0 decays/min (which is small compared with background radiation). How long will the building be unsafe?

[6]

END OF PAPER