UNIVERSITY OF SWAZILAND

FACULTY OF SCIENCE

181

DEPARTMENT OF PHYSICS

MAIN EXAMINATION: 2011/2012

TITLE OF THE PAPER: NUCLEAR PHYSICS

COURSE NUMBER: P442

TIME ALLOWED: THREE HOURS

INSTRUCTIONS:

- ANSWER ANY FOUR OUT THE FIVE QUESTIONS.
- EACH QUESTION CARRIES 25 MARKS.
- MARKS FOR DIFFERENT SECTIONS ARE SHOWN IN THE RIGHT-HAND MARGIN.
- USE THE INFORMATION GIVEN IN THE ATTACHED APPENDIX WHEN NECESSARY.

THIS PAPER HAS 8 PAGES, INCLUDING THIS PAGE.

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General Data:

1 unified mass unit (u) $=1.6605 \times 10^{-27}$kg $= 931.5$ MeV/c^2
Planck's constant $h = 6.63^{-34}$Js
Boltmann's constant $k = 1.38 \times 10^{-23} JK^{-1}$
Avogardo's number 6.022×10^{23} (g-mole)$^{-1}$
speed of light (vacuum) $c = 3.0 \times 10^8$ m/s
electron mass $= 9.11 \times 10^{-31}$kg $= 5.4858^{-4}$u $= 0.511$ MeV/c^2
neutron mass $= 1.6749 \times 10^{-27}$kg $= 1.008665$ u $= 939.573$ MeV/c^2
proton mass $= 1.6726 \times 10^{-31}$kg $=1.0072765$ u $=938.280$ MeV/c^2
1 year $= 3.156^7$ s
nuclear radius, R $\cong r_0 A^{1/3}$, where $r_0 = 1.2$ fm

The table of nuclear properties is provided in the following page.

Nuclide	Z	A	Atomic mass (u)	I^π	Abundance or Half life
H	1	1	1.007825	$1/2^+$	99.985%
He	2	4	4.002603	0^+	99.99986%
Li	3	7	7.016003	$3/2^-$	92.5%
Be	4	11	11.021658	$1/2^+$	13.8s(β^-)
B	5	11	11.009305	$3/2^-$	80.2%
C	6	12	12.000000	0^+	99.89%
N	7	15	15.000109	$1/2^-$	0.366%
N	7	18	18.014081	1^-	0.63 s
O	8	15	15.003065	$1/2^-$	122 s (e)
O	8	16	15.994915	0^+	99.76%
O	8	18	17.999160	0^+	0.204%
F	9	18	18.000937	1^+	110.0 min
Ne	10	20	19.992436	0^+	90.51%
Ne	10	22	21.991383	0^+	9.33%
Na	11	22	21.994434	3^+	2.60 yrs
Mg	12	22	21.000574	0^+	3.86 s
Al	13	27	26.981539	$5/2^+$	100.00 %
Si	14	22	29.973770	0^+	3.10%
Si	14	32	31.974148	0^+	105y
P	15	30	29.978307	1^+	2.50min
P	15	32	31.971725	1^+	14.3d
S	16	32	31.972071	0^+	95.02%
Cl	17	37	36.965903	$3/2^+$	24.23%
Ar	18	37	36.966776	$3/2^+$	35.0 d
K	19	37	36.973377	$3/2^-$	1.23 s
Ca	20	43	42.958766	$7/2^-$	0.135%
Ca	20	47	46.954543	$7/2^-$	4.54 d (β^-)
Sc	21	47	46.952409	$7/2^-$	3.35 d (β^-)
Fe	26	56	55.934439	0^+	91.8%
Fe	26	60	59.934078	0^+	1.5My
Co	27	60	59.933820	5^+	5.27y
Ni	28	60	59.930788	0^+	26.1%
Ni	28	64	63.927968	0^+	0.91%
Ni	28	65	64.930086	$5/2^-$	2.52 h (β^-)
Cu	29	63	62.929599	$3/2^-$	69.2%
Cu	29	64	63.929800	1^+	12.7 h
Cu	29	65	64.927793	$3/2^+$	30.8%
Zn	30	64	63.929145	0^+	48.6%
Ru	44	104	103.905424	0^+	18.7%
Ru	44	105	104.907744	$3/2^+$	4.44h (β^-)
Pd	46	105	104.905079	$5/2^+$	22.2%
Cs	55	137	136.907073	$7/2^+$	30.2 y (β^-)
Ba	56	137	136.905812	$3/2^+$	11.2%
Tl	81	203	202.972320	$1/2^+$	29.5%
Os	76	191	190.960920	$9/2^-$	15.4 d (β^-) %
Ir	77	191	190.960584	$3/2^+$	37.3%
Au	79	199	198.968254	$3/2^+$	16.8%

Question 1

(a) The lowest energy levels in the Shell Model, in order of increasing energy are

$$1s_{1/2},\ 1p_{3/2},\ 1p_{1/2},\ 1d_{5/2},\ 2s_{1/2}, 1d_{3/2},\ 1f_j,\ ....$$

(i) What are the possible values of j for the $1f$ levels.

[2 marks]

(ii) What is the value of j for the lowest $1f$ level? Justify your answer.

[2 marks]

(iii) Determine the spin and parity of the ground state of both the $^{40}_{20}Ca$ and $^{41}_{20}Ca$ nuclides.

[8 marks]

(iv) In the Shell model, a 'spin-orbit' interaction splits all the energy levels except the 's-type' levels. Why do the s-type levels remain unsplit?

[1 marks]

(b) The low-lying energy levels of ^{13}C are the ground state ($\frac{1}{2}^-$); 3.09MeV ($\frac{1}{2}^+$); 3.68MeV ($\frac{3}{2}^-$) and 3.85MeV ($\frac{5}{2}^+$). Interpret these states according to the shell-model.

[12 marks]

Question 2

(a) Using the observation the nuclear radius $r = r_0 A^{1/3}$, estimate the average mass density of a nucleus.

[3 marks]

(b) Describe *briefly* the 'origin' of the various terms in the Semi-Empirical Mass Formula. [NB: detailed mathematical expressions and values of constants are not required].

[5 marks]

(c) Suggest a simple reason why the ${}^{12}_{6}C$ nuclide has a higher binding energy (i.e. more stable) than ${}^{12}_{7}N$, even though they are isobars?

[3 marks]

(d) Given that the stable sodium isotope is ${}^{23}_{11}Na$, what type of radioactivity would you expect from

(i) ${}^{22}Na$

(ii) ${}^{24}Na$

[6 marks]

(e) Supply the missing particles in the following processes

(i) $\bar{\nu} + {}^{3}He \rightarrow$

[2 marks]

(ii) $e^{-} + {}^{8}B \rightarrow$

[2 marks]

(iii) ${}^{40}K \rightarrow \bar{\nu}$

[2 marks]

(iv) $\nu + {}^{12}C \rightarrow$

[2 marks]

Question 3

(a) A by-product of some fission reactors is ^{239}Pu which is an α-emitter with a half-life of 24,120 years. Consider 1 kg of ^{239}Pu at t=0.[Atomic mass of ^{239}Pu = 239.052163u].

(i) What is the number of ^{239}Pu nuclei at t=0?

[2 marks]

(ii) What is the initial activity?

[2 marks]

(iii) For how long would you need to store Plutonium until it has decayed to a safe activity level of 0.1 Bq?

[3 marks]

(b) Radionuclides are useful sources of small amounts of energy in space vehicles, remote communication stations, heart pacemakers etc. Calculate the power available in Watts from a gram of ^{210}Po, an α-emitter with an energy of 5.30 MeV and a half life of 138 days. [Atomic mass of $^{210}_{84}Po$ =209.982848 u].

[5 marks]

(c) In stars slightly more massive than the Sun, hydrogen burning is carried out mainly by the CNO cycle, whose first step is $p +^{12}_{6} C \rightarrow^{13}_{7} N + \gamma$. Estimate the energy of the gamma (in MeV), assuming the two initial nuclei are essentially at rest. Justify any simplifying assumptions you make. [Atomic masses:$^{1}_{1}H = 1.007825u,^{12}_{6} C = 12.000000u,^{13}_{7} N = 13.005739u$].

[4 marks]

(d) Consider the nuclear fission reaction $n +^{235}_{92} U \rightarrow^{141}_{56} Ba +^{92}_{36} Kr + 3n$.

(i) Calculate the energy released (in MeV) in the reaction. [Atomic masses: $^{235}_{92}U$ = $235.043915u$, $^{141}_{56}Ba = 140.9139u$, $^{92}_{36}Kr = 91.8973u$. The neutron mass is 1.008665u].

[4 marks]

(ii) You wish to run a 1000MW power reactor using $^{235}_{92}U$ fission. How much $^{235}_{92}U$ is required for one day's operation?

[5 marks]

Question 4

(a) For the following γ transitions, give all permitted multipoles and indicate which multipole might be most intense in the emitted radiation.

(i) $\frac{9}{2}^- \rightarrow \frac{7}{2}^+$

(ii) $\frac{1}{2}^- \rightarrow \frac{7}{2}^-$

(iii) $1^- \rightarrow 2^+$

(iv) $4^+ \rightarrow 2^+$

(v) $\frac{11}{2}^- \rightarrow \frac{3}{2}^+$

[5 marks]

(b) Explain why a transition from 0^+ to 0^+ will not allow any γ radiation.

[2 marks]

(c) An even-Z, even-N nucleus has the following sequence of levels above its 0^+ ground state:

$$2^+(89keV),\ 4^+(288keV),\ 6^+(585keV),\ 0^+(1050keV),\ 2^+(1129keV)$$

Draw an energy level diagram and show all reasonably probable γ transitions and their dominant multipole assignments.

[10 marks]

(d) Given the following radio-nuclides:

$$^{60}_{27}Co,\ ^{32}_{15}P$$

Show by actual calculation, which of these nuclides will decay by

(i) β^+ emission

[4 marks]

(ii) electron capture

[4 marks]

Question 5

(a) Write brief notes on the following instruments

(i) Geiger-muller counter

(ii) Scintillation detector

[6 marks]

(b) Discuss three modes by which a photon can interact with matter.

[6 marks]

(c) Discuss the essential features of the strong nuclear force

[4 marks]

(d) Show that the decay $n \to p + e^-$ cannot conserve angular momentum.

[3 marks]

(e) Write short note on the following

(i) Internal conversion

(ii) Bremsstrahlung

[6 marks]