UNIVERSITY OF SWAZILAND

FACULTY OF SCIENCE

DEPARTMENT OF PHYSICS

MAIN EXAMINATION 2008-09

TITLE OF THE PAPER: NUCLEAR PHYSICS

COURSE NUMBER : P442

TIME ALLOWED : THREE HOURS

INSTRUCTIONS:

- **ANSWER ANY FOUR OUT OF 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 SIX PAGES, INCLUDING THIS PAGE.

DO NOT OPEN THE PAPER UNTIL THE INVIGILATOR HAS GIVEN PERMISSION.

Q.1. (A) Consider an isotope of atomic mass M(Z,A) where Z=atomic number, A=Z+N = mass number, and N = neutron number.

(i) Define mass defect. **[1]**
(ii) Define nuclear binding energy. **[1]**
Give an expression of the binding energy in terms of
- **(a)** Nuclear masses. **[1]**
- **(b)** Atomic masses. **[1]**

(iii) Define Q value for β^- , β^+ and electron capture. **[3]**

(iv) The ${}^{22}_{11}Na$ (atomic mass = 20487..686 MeV) decays by β^+ emission and electron capture(EC) to first excited state of ${}^{22}_{10}Ne$ (atomic mass=20484.844 MeV). Calculate the β^+ decay Q-value and the EC decay Q-value in MeV. **[4]**

(B)

(i) Define half life, mean life, decay constant and activity. **[4]**

(ii) Write a brief note on " Radioactive Dating". **[5]**

(iii) A 0.001 kg sample from an organic artefact is found to have a β count rate of 2.1 counts per minute, which are assumed to originate from the decay of ${}^{14}_{6}C$ with a mean life time of 8270 years. If the abundance of ${}^{14}_{6}C$ in living matter is currently 1.2×10^{-12} , calculate the approximate age of the artefact. **[5]**

Q.2.

(A) Write brief notes on any two of the following:
- **(i)** Scintillation detector. Explain why NaI crystal is doped with Tl . **[5]**
- **(ii)** Fission and Fusion. **[5]**
- **(iii)** Describe the significant processes through which the γ-rays in the energy range greater than 5 MeV primarily interact with matter. **[5]**

(B) (i) Among the possible interactions : **[2]**

S(scalar),V(vector),T(Tensor),A(axial vector) and P(pseudo-scalar);

name the interactions which are the major contributors in Fermi type and GT-type β- transitions. What is the implication of the interactions on selection rules (the Fermi and GT) β-decay.

(ii) State the conservation laws in weak interactions. Use the relevant conservation law to supply the missing component(s) in the following processes. Use the symbol X for the needed nuclei in the missing components. **[4]**

(a) ${}^{40}_{19}K \rightarrow \nu +$

(b) ${}^{40}_{19}K \rightarrow \bar{\nu} +$

(iii) ${}^{137}_{55}Cs$ with its ground state $7/2^+$ decays by beta-decay to $11/2^-$ and $3/2^+$ states of ${}^{137}_{56}Ba$. What types of transitions are expected in each case? **[4]**

Q.3. Semi-empirical mass formula for nuclear mass *m(Z,A)* is given by

$$m(Z,A) = Zm_p + (A-Z)m_n - a_v A + a_s A^{2/3} + a_c Z^2 A^{-1/3} + a_a \frac{(A-2Z)^2}{A} + \delta\, A^{-1/2}$$

with a_v = 15.56 MeV , a_s = 17.23 MeV , a_c = 0.697 MeV , a_a = 23.20 MeV, and
δ = 11.2 MeV for odd-odd
= 0 for odd-even or even-odd.
= -11.2 MeV for even -even

(i) Explain the origin of various terms in the given semi-empirical mass formula. **[10]**

(ii) Define Q value for α-particle emission in terms of mass m(Z,A) of parent nucleus and m(Z-2,A-4) of daughter nucleus. **[1]**

(a) What is the relation between separation energy for α-particle and Q-value. **[1]**

(b) What is the relation between Q value and kinetic energy of the emitted α- particle (E_α) and the kinetic energy of the daughter nucleus (E_D) . **[1]**

(c) Consider energy momentum conservation in α -decay to show that **[5]**

$$Q = E_\alpha \left[1 + \frac{m(2,4)}{m(Z-2,A-4)}\right]$$

(iii) The transuranic isotope ${}^{269}_{108}Hs$ decays 100 percent via α emission. **[7]**

$${}^{269}_{108}Hs \Rightarrow {}^{265}_{106}Sg + \alpha$$

The kinetic energy of α-particle is E_α = 9.23 MeV.
Calculate the Q-value (also known as total energy) involved in α-decay of ${}^{269}_{108}Hs$.
Hence calculate the recoil energy of daughter nucleus.

Assume $\frac{m(2,4)}{m(106,265)} = 0.01510$

Q.4.

(A) (i) The ground state of ${}^{73}_{35}Br$ has $J^P = \frac{1}{2}^-$ and the first two excited states have $J^P = \frac{5}{2}^-$ (26.92 keV) and $J^P = \frac{3}{2}^-$ (178.1 keV).

(a) List the possible γ-transitions between these levels. **[6]**
(b) Predict the most probable transitions. **[3]**
(c) Draw the energy level diagram. **[1]**

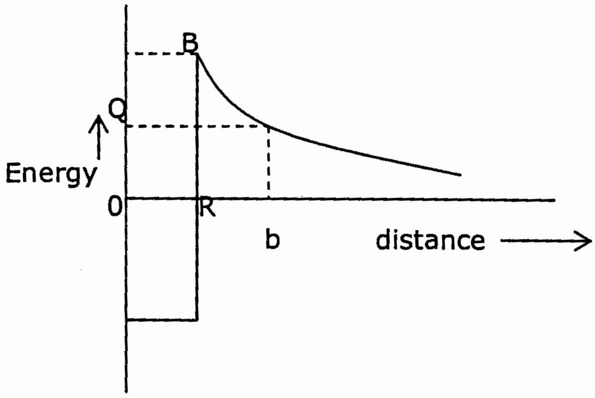
(ii) Explain why transition from 0^+ to 0^+ will not allow any γ -radiation. **[3]**

(B) A nuclei X with spin-parity $\frac{5}{2}^+$ decays by α-particle emission to the following states in nuclei Y with spin-parity **[6]**

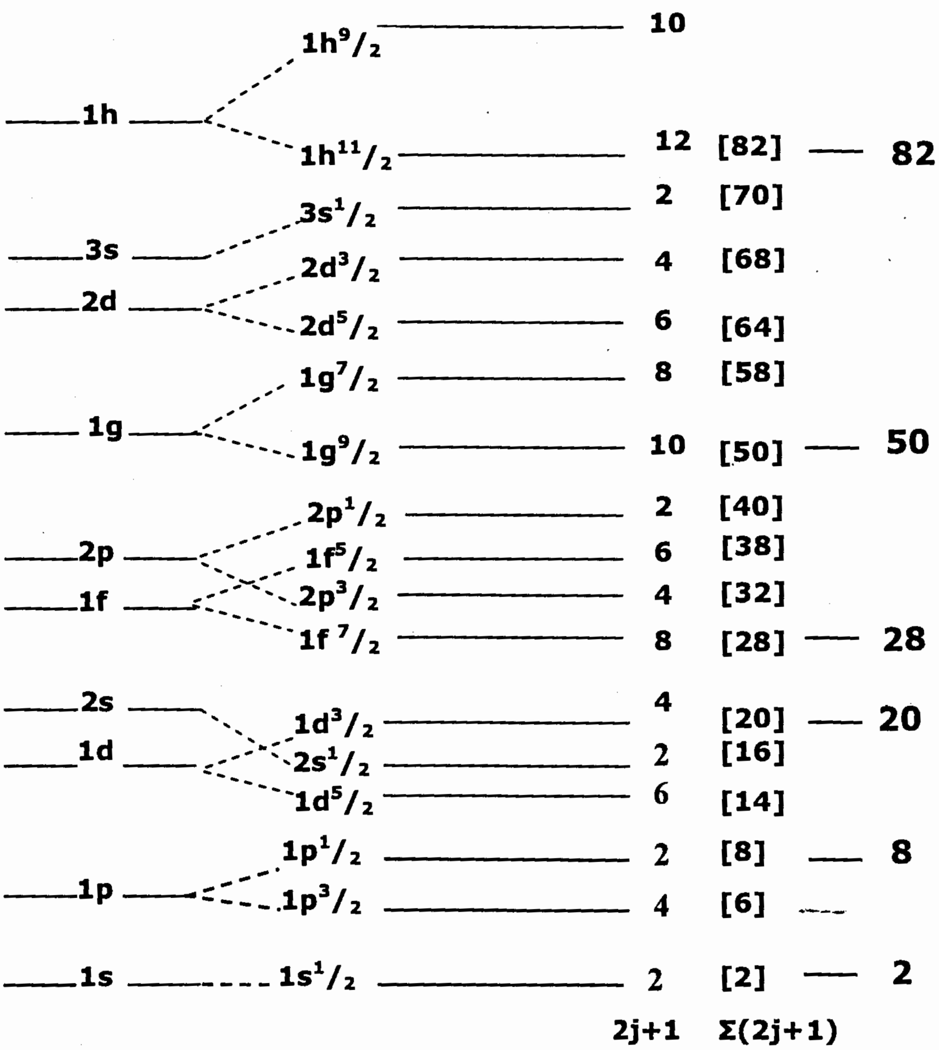
$$\frac{3}{2}^+ \;,\; \frac{5}{2}^- \;,\; \frac{7}{2}^-$$

Assume that the ground state of Y to be $3/2^+$ and remaining states according to the order given in the spin assignments. For each state find the permitted value of orbital angular momentum ℓ_α for α-particle.

(C) The alpha-decay Q-value of 238U is 4.268 MeV. Calculate the height B of the Coulomb barrier between the alpha-particle and the daughter nucleus, assuming that the nuclear potential has a sharp edge at a radius of $1.4A^{1/3}$ fm. Calculate the distance b beyond which the alpha-particle kinetic energy is positive. **[6]**



Q.5. (A) Following diagram gives the energy levels calculated using a realistic potential with spin-orbit interaction according to single particle shell model:



(i) What do you understand by the term " Magic Numbers" ? **[2]**

(ii) Explain how the spin and parities are determined using the single particle shell model for even-even, odd-even, even-odd and odd-odd nuclei. **[4]**

(iii) What are the configurations of the ground states of the nuclei $^{93}_{41}Nb$ and $^{33}_{16}S$ and what values are predicted in the single particle shell model for their spins and parities? **[6]**

(iv) What are the parities and upper and lower limits for the spins for the ground states of nuclei $^{6}_{3}Li$, $^{14}_{7}N$ *and* $^{28}_{13}Al$? **[6]**

(B) Describe the nature of nucleon-nucleon force with reference to the explanation of deuteron properties, namely, binding energy, magnetic moment and finite quadrupole moment. **[7]**

@@@END OF EXAMINATION@@@

Appendix

Selection Rules:

(A) β-decay:

Type of Transition		ΔI	Parity Change
Allowed	Fermi	0	No
	GT	± 1 or 0 (except 0 → 0)	No
1st Forbidden	Fermi	± 1,0 (except 0 → 0)	Yes
	GT	±2, ± 1, or 0 (except 0 → 0; 1/2→1/2; 0→ 1)	Yes
2nd Forbidden	Fermi	± 2	No
	GT	± 3	No

(B) γ- decay:

	E1	E2	E3	E4
Δπ	Yes	No	Yes	No
|ΔJ| ≤	1	2	3	4
	M1	M2	M3	M4
Δπ	No	Yes	No	Yes
|ΔJ| ≤	1	2	3	4

(C) Useful Information

PHYSICAL CONSTANTS [1] AND DERIVED QUANTITIES

Speed of light c = 2.99792458×10^{8} m s^{-1} ~ 3.00×10^{23} fm s^{-1}
Avogadro's number N_A = $6.02214199(47) \times 10^{26}$ molecules per kg-mole
Planck's constant h = $6.626068\ 76(52) \times 10^{-34}$ J s
$\hbar = 1.054571\ 596(82) \times 10^{-34}$ J s = 0.65821×10^{-21} MeV s
$\hbar^2 = 41.802$ u MeV fm^2
$\hbar c = 197.327$ MeV fm

Elementary charge $e = 1.602176462(63) \times 10^{-19}$C
$e^2/4\pi\varepsilon_0 = 1.4400$MeV fm

Fine structure constant $\alpha = \dfrac{e^2}{4\pi\varepsilon_0\hbar c} = 1\ /\ 137.036$

Boltzmann constant $k = 1.3806503(24) \times 10^{-23}$ JK^{-1} = 0.8617×10^{-4} eV K^{-1}

USEFUL FORMULAE

$t_{1/2} = \dfrac{\ell n2}{\lambda} = \tau\,\ell n2$ where $t_{1/2}$ = half life, λ = decay constant and τ = mean life .

Energy width of a state of lifetime τ :

$\Gamma = 6.58212 \times 10^{-22} / \tau(s)$ MeV

Non-relativistic speed of mass m **with energy** E:

$v = 1.389 \times 10^7\ [(E(MeV)\ /\ m(u)\ ]^{1/2}$ ms^{-1}

Non-relativistic wave number of mass m **with energy** E:

$k \equiv 2\pi/\lambda = 0.21874\ [\ m(u) \times E(MeV)\ ]^{1/2}$ fm^{-1}

Wave number for a photon of energy E:

$k \equiv 2\pi/\lambda = E/\hbar c = E$ (MeV) / 197.327 fm^{-1}

MASSES AND ENERGIES

Atomic mass unit m_u or u = $1.66053873(13) \times 10^{-27}$ kg
$m_u c^2 = 931.494$ MeV

Electron	m_e	$= 9.10938188(72) \times 10^{-31}$ kg
	m_e/m_u	$= 5.486 \times 10^{-4} = 1/1823$
	$m_e c^2$	$= 0.510998902(21)$ MeV
Proton	m_p	$= 1.67262158(13) \times 10^{-27}$ kg
	m_p / m_u	$= 1.00727647$
	$m_p c^2$	$= 938.272$ MeV
Hydrogen atom	m_H	$= 1.673533 \times 10^{-27}$ kg
	m_H / m_u	$= 1.007825$
	$m_H c^2$	$= 938.783$ MeV
Neutron	m_n	$= 1.67492716(13) \times 10^{-27}$ kg
	m_n/m_u	$= 1.00866491578(55)$
	$m_n c^2$	$= 939.565$ MeV
Alpha particle	m_α	$= 6.644656 \times 10^{-27}$ kg
	m_α / m_u	$= 4.001506175$
	$m_\alpha c^2$	$= 3727.379$ MeV

CONVERSION FACTORS

Fermi 1fm = 10^{-15} m		
1 eV=1.6022 x 10^{-9} J		
Million electron volts	1 MeV	$= 1.602176 \times 10^{-13}$ J
	1 MeV/c^2	$= 1.783 \times 10^{-30}$ kg
Cross section (barn)	1 b	$= 10^{-28}$ m^2
Year	l y	$= 3.1536 \times 10^7$ s