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KEELE UNIVERSITY

EXAMINATIONS, 2011/12

Level II

Thursday 17th May 2012, 09:30-11:30

PHYSICS

PHY-20009

NUCLEAR AND PARTICLE PHYSICS

Candidates should attempt to answer FOUR questions.

NOT TO BE REMOVED FROM THE EXAMINATION HALL

1. (a) Describe the following types of particles, with reference to th internal structure:

   i. hadrons [5]

   ii. baryons [5]

   iii. mesons [5]

   iv. leptons [5]

   (b) Determine all possible quark sub-structures of zero charm particles with the following properties:

   i. strangeness of -2 and negative charge, [20]

   ii. strangeness of -1 and zero charge. [25]

   iii. The Ξ^- particle is the lightest possible particle with strangeness of -2 and the Σ^0 is the lightest possible particle with strangeness of -1. Identify the quark structure of both particles. [10]

   (c) The Ξ^- particle decays to the Σ^0 particle as follows:

$$\Xi^- \rightarrow \Sigma^0 + e^- + \bar{\nu}_e$$

   i. Draw a Feynman diagram for the decay and show which non-zero quantities (e. g. charge) are conserved at each vertex and which ones are not. [20]

   ii. What other weak decay mode is possible from the Ξ^- particle to the Σ^0 particle? [5]

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2. (a) Describe how a plot of the difference between the two-neut separation energy and the semi-empirical mass formula prediction versus neutron number provides evidence for a shell model of nuclei. [20]

(b) State what is meant by a *magic number* in the shell model. [5]

(c) Explain why the plot of part (a) is more useful than an equivalent plot using one-neutron separation energy. [5]

(d) The lowest shell model states are, in order of increasing energy:

$$1s_{1/2} \quad 1p_{3/2} \quad 1p_{1/2} \quad 1d_{5/2} \quad 2s_{1/2} \quad 1d_{3/2}$$

$$1f_{7/2} \quad 2p_{3/2} \quad 1f_{5/2} \quad 2p_{1/2} \quad 1g_{9/2}\,.$$

i. Draw a shell model diagram for ^{57}Ni and predict with explanation its ground state spin and parity. [40]

ii. The first 3 excited states of ^{57}Ni are $5/2^-$ at 0.769 MeV, $1/2^-$ at 1.113 MeV and $5/2^-$ at 2.443 MeV. To what extent can these 3 states be explained using the shell diagram from part (d) i.? [30]

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3. The energies in units of MeV, spins and parities of low lying exc states in some nuclei are given as follows:

State:	1st		2nd		3rd		4th	
^{26}Mg:	1.809	2^+	2.938	2^+	3.589	0^+	3.942	3^+
^{102}Ru:	0.475	2^+	0.944	0^+	1.103	2^+	1.106	4^+
^{176}Hf:	0.088	2^+	0.290	4^+	0.597	6^+	0.998	8^+

(a) State and explain the spin and parity for the *ground* state of these nuclei. [15]

(b) Using the information in the table above, describe and explain which nuclear model is most applicable to each of these three nuclei. [45]

(c) Calculate, using the most appropriate excited state, best estimates for:

i. the phonon frequency for the vibrational nucleus and [20]

ii. the moment of inertia of the rotational nucleus. (Hint: the expectation value of the square of the total nuclear spin, $\left\langle \vec{I}^2 \right\rangle = \hbar^2 I(I+1)$.) [20]

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4. (a) State briefly the mechanism by which a nucleus undergoes α decay and explain the range of values between which the Q value must lie. [20]

(b) The decay constant for α decay is given approximately by:

$$\lambda = P\,f\,e^{-2G}$$

where P is the preformation probability, f is the frequency with which the α particle encounters the Coulomb barrier and G is the Gamow factor. For ^{241}Am α decay, $f = 4.17 \times 10^{21}$ Hz and $G = 35.2$. Determine the minimum possible half life given by the above formula. [15]

(c) When ^{241}Am decays, 85% of the decays lead to the 59.5 keV $5/2^-$ second excited state in ^{237}Np. Assuming that de-excitation occurs via the lowest multipolarity γ decay, determine whether the emitted γ ray is electric or magnetic, and its multipolarity for:

i. de-excitation of the 59.5 keV excited state to the $5/2^+$ ground state, [20]

ii. de-excitation of the 59.5 keV excited state to the 33.2 keV $7/2^+$ state, [10]

iii. de-excitation of the 33.2 keV excited state to the $5/2^+$ ground state. [10]

(d) 94% of de-excitations of the ^{237}Np 59.5 keV state proceed directly to the ground state. Calculate how many 59.5 keV γ rays would be expected to be emitted from a 100 kBq ^{241}Am α source over a period of 1 hour. [25]

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5. (a) For the following reactions, replace the question mark with appropriate nucleus or particle and name which reaction category they belong to.

   i. $^{23}\mathrm{Na}(\mathrm{d},\mathbf{?})^{21}\mathrm{Ne}$ [10]

   ii. $^{139}\mathrm{La}(\mathbf{?},{}^{12}\mathrm{C})^{139}\mathrm{La}$ [10]

   iii. $^{12}\mathrm{C}(\alpha,\gamma)\mathbf{?}$ [10]

(b) Using the information below, calculate the Q value for the $^{28}\mathrm{Si}(\alpha,{}^{16}\mathrm{O})^{16}\mathrm{O}$ reaction. [10]

	u (1u=931.5 MeV/c^2)
^{4}He	4.002603
^{16}O	15.994915
^{28}Si	27.976927

(c) In the laboratory frame, where a projectile of mass m_a and kinetic energy T_a is incident on a stationary target nucleus, the ejectile kinetic energy T_b at angle θ_b may be determined from

$$\sqrt{T_b} = \frac{F \pm \sqrt{F^2 + (m_Y + m_b)[m_Y Q + (m_Y - m_a)T_a]}}{m_Y + m_b}$$

where

$$F = \cos\theta_b \sqrt{m_a m_b T_a}$$

m_b and m_Y are the masses of the ejectile and residual nucleus respectively and Q is the reaction Q value. For the reaction in part (b):

   i. define and calculate the threshold energy, [40]

   ii. determine the range of projectile energies for which there are two possible ejectile energies. [20]

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6. (a) Describe briefly the process of neutron-induced fission, expla ing the two stages by which it occurs and define activation and excitation energies. [20]

(b) Calculate the excitation energy for thermal-neutron-induced fission on ^{233}U and ^{237}Np. [20]

(c) The activation energies for the target nuclei in part (b) are 6.5 MeV and 6.2 MeV, respectively. For both ^{233}U and ^{237}Np, either:

- if the fission can proceed, determine the Q-value considering that the compound nucleus releases two neutrons, ^{140}Xe and another fragment; or
- if the fission cannot proceed, determine the minimum neutron kinetic energy needed to induce fission. [40]

(d) Considering that the neutrons carry a negligible amount of momentum/kinetic energy, determine the ratio between the kinetic energy of the two fragments for one case from (c) for which fission is induced with thermal neutrons. [20]

Additional data:

Neutron and atomic masses in u (1u=931.5 MeV/c^2)

n	1.008665	^{233}U	233.039628
^{92}Sr	91.910944	^{234}U	234.040947
^{96}Y	95.915891	^{237}Np	237.048168
^{140}Xe	139.921640	^{238}Np	238.050941