PH20016 “Particles, Nuclei and Stars”

Mock Test

24 November 2022

18 marks for 30 minutes – Exam: 60 marks

2. Explain briefly …
(a) the 4 different ways in which neutrons can interact with a heavy nucleus
(b) what is referred to as a nuclear resonance
(c) the role of a moderator in a nuclear reactor

[4 marks]

1. For each of the following reactions, check whether it violates any conservation law (and state which one(s) are violated):

(a) $p + p \rightarrow p + p + \pi^0$

(b) $p + p \rightarrow \pi^0 + p + n + n$

(c) $p \rightarrow e^+ + \gamma$

[3 marks]

(adapted from 2007/8 exam)

Reaction (a) conserves charge. We do not know about the momentum. The energy is conserved if adding enough kinetic energy. Quark flavour is conserved. Baryon numbers and lepton numbers are conserved. Therefore, reaction (a) may occur. 1 mark

Reaction (b) does not conserve baryon numbers + charge ½ + ½ mark

Reaction (c) does not conserve baryon and lepton numbers. ½ + ½ mark *(adapted from 2008/9 exam)* **Question 2**

The number (e.g. 1, 2) corresponds to the energy level in the shell model. The letter corresponds to the orbital angular momentum quantum number. The subscript corresponds to the total angular momentum.

The number of nucleons in each level is 2j + 1 (cf. lecture notes).

Therefore:

Level	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$
j	1/2	3/2	1/2	5/2	1/2	3/2
No. of nucleons	2	4	2	6	2	4

${}^4_2He$: 2 protons, 2 neutrons $\Rightarrow$ both $1s_{1/2}$ shells are filled: $\underline{J = 0}$ 1 mark

${}^9_4Be$: 4 protons $\Rightarrow$ $1s_{1/2}$ shell is filled, 2 protons in shell $1p_{3/2}$

5 neutrons $\Rightarrow$ $1s_{1/2}$ shell is filled, 3 neutrons in shell $1p_{3/2}$. one of which is unpaired: $\underline{J = 3/2}$. 1 mark

${}^9_4Be^*$: first excited state corresponds to the unpaired neutron being raised to the next energy level (i.e. $1p_{1/2}$) $\Rightarrow$ $\underline{J = 1/2}$

1 mark

(from 2013 exam)

Question 3

An atom of ${}^{238}_{92}U$ passing through matter interacts mainly with the neutrons in the nuclei, and has a total cross-section of 1.45 barns. Assuming that half of the mass of a typical piece of matter is due to neutrons and that all of the neutrons in a nucleus act independently, work out the probability that the uranium atom will interact as it passes through your finger.

Mean human density: 325.58 kg/m^3

Mean diameter of a human finger: 1 cm

[6 marks]

Unseen question – Slightly higher challenge

For information, I calculated the mean density of a human being assuming: mass = 70 kg, height = 1.72 m, depth = 0.25 m, width = 0.5 m (i.e. a parallepiped, however approximate that is, with a volume = 0.215 m^3).

The mean free path is given by: $l_0 = \dfrac{1}{\rho_{nuc}\,\sigma}$

ρ_{nuc}, in this case, is the density of neutrons. It is given by:

$$\rho_{nuc} = \frac{\frac{1}{2}(325.58)}{mass\ of\ neutron}\ m^{-3} = \frac{1}{2}\,\frac{325.58}{1.67\times10^{-27}} = 9.7479\times10^{28}\ m^{-3} \qquad \therefore l_0 = \frac{1}{9.7479\times10^{28}\times1.45\times10^{-28}}\ m$$

$$l_0 = 0.0707\ m$$

$\therefore$ *mean free path is much smaller than the height of the person*

The probability of interaction is (h being the height):

$$\rho_{nuc}\ \sigma\ d = \frac{d}{l_0} = \frac{0.01}{0.0707} = 0..1414,\ i.e.\ less\ than\ 14.14\ \%$$

6 marks

Or: 4 marks if right formula and calculation mistake

Or: 2 marks if only right formula

Or: 0 mark if not right formula and wrong numbers

(i) The two decays (2) and (5), taken together, release a total energy of 2.9 MeV. Assuming that positrons annihilate with electrons in the stellar plasma, calculate the energy released in the other reactions of the CNO chain and hence the overall energy released by this chain.

Green: marks for partial answers

[6 marks]

(direct from 2010/11 exam)

The energy released by each reaction, Q_i, equals the binding energy of the products, minus the binding energy of the reactants (cf. lecture notes and problem sheets):

$Q_1 = B({}^{13}_{7}N) - B({}^{12}_{6}C) = 94.1 - 92.2 = 1.9\ MeV$ 1 mark

$Q_2 + Q_5 = 2.9\ MeV$ *(given in text)*

$Q_3 = B({}^{14}_{7}N) - B({}^{13}_{6}C) = 104.7 - 97.1 = 7.6\ MeV$ 1 mark

$Q_4 = B({}^{15}_{8}O) - B({}^{14}_{7}N) = 112.0 - 104.7 = 7.3\ MeV$ 1 mark

$Q_6 = B({}^{12}_{6}C) + B({}^{4}_{2}He) - B({}^{15}_{7}N) = 92.2 + 28.3 - 115.5 = 5.0\ MeV$ 1 mark

Annihilation of positrons with electrons releases $2m_ec^2 = 2 \times 0.511$ MeV each time.

2 positrons are created in each occurrence of the CNO chain (i.e. 2×1.022 MeV). 1 mark

Total energy release during the CNO chain is therefore:

$Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + 2 \times 2m_ec^2 = 26.744\ MeV$

Right answer: 6 marks

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(b) what is referred to as a nuclear resonance
(c) the role of a moderator in a nuclear reactor

[4 marks]

Question 2

2. Explain briefly …

(a) the 4 different ways in which neutrons can interact with a heavy nucleus

2 marks

0.5 mark each

[1] Elastic scattering: scattering in which overall KE is conserved (because of target recoil, neutron will lose some KE)

[2] Inelastic scattering: scattering in which KE is not conserved, as heavy nucleus is left in excited state

[3] Radiative capture: neutron is absorbed and photon emitted (n+ ${}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X^{*} + \gamma$)

[4] Fission: neutron leaves target at energy state above spontaneous fission barrier leading it to break up

(b) what is referred to as a nuclear resonance

1 mark

An excited state of a stable particle causing a sharp maximum in the cross section at a specific energy for an incoming particle (neutron, photon, …).

(c) the role of a moderator in a nuclear reactor

1 mark

A moderator consists of target nuclei that serve to slow down fast neutrons resulting from a fission process by interacting with them, thus bringing them to low energies where the cross section for inducing further fission is higher.

[4 marks]