Nuclear Physics Revision Problems

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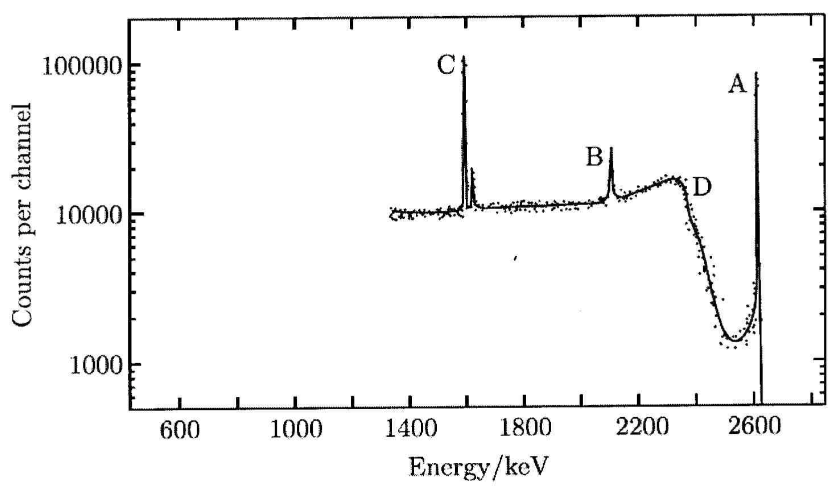
1. (a) When a photon interacts with an atom, it can lose energy by Compton scattering, the photoelectric effect, or electron-positron pair production. Draw Feynman diagrams for each of these processes.
(Hint: Not all are possible in the absence of the atomic nucleus.)

   (b) Show that, for Compton scattering off a stationary free electron, the maximum energy which can be transferred to the electron is given by

$$\Delta E = \frac{2E_\gamma^2}{m_e c^2 + 2E_\gamma}$$

The figure below shows the energy deposited in a detector by photons coming from gamma decay of ^{24}Na.



   (c) What is the energy of the incoming photons?

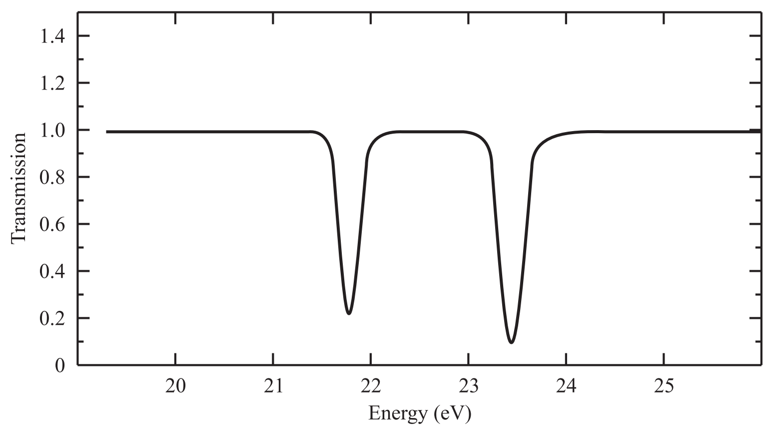
   (d) Explain the physical origin of the peaks labelled A, B, C and the edge labelled D.

2. (a) Nucleons are fermions and therefore respect the Pauli exclusion principle. The number of states (integrated density of states) $\mathcal{N}(E_F)$ for fermions in a volume V with energies $E < E_F$ is given by

$$\mathcal{N}(E_F) = \frac{V}{3\pi^2}\left(\frac{2\,m_N E_F}{\hbar^2}\right)^{\frac{3}{2}},$$

where m_N is the nucleon mass and E_F the Fermi energy. Assuming a spherical nuclear volume with radius R, estimate E_F for neutrons in a nucleus with neutron number $N = A/2$. What is the speed v of the neutrons with energies near E_F and the corresponding nuclear timescale defined by $2R/v$? You may assume that $R = r_0 A^{\frac{1}{3}}$ where $r_0 = 1.2\,\text{fm}$.

(b) The diagram shows detail from a transmission measurement of low-energy neutrons incident on ^{232}Th. From the diagram estimate the values of E_0 and Γ for the two resonances and thus estimate the lifetimes of the states. Comment on any differences between these values and the estimate of the nuclear timescale from the first part of the question.



3. (a) Why are antineutrinos (and not neutrinos) produced by a fission reactor?

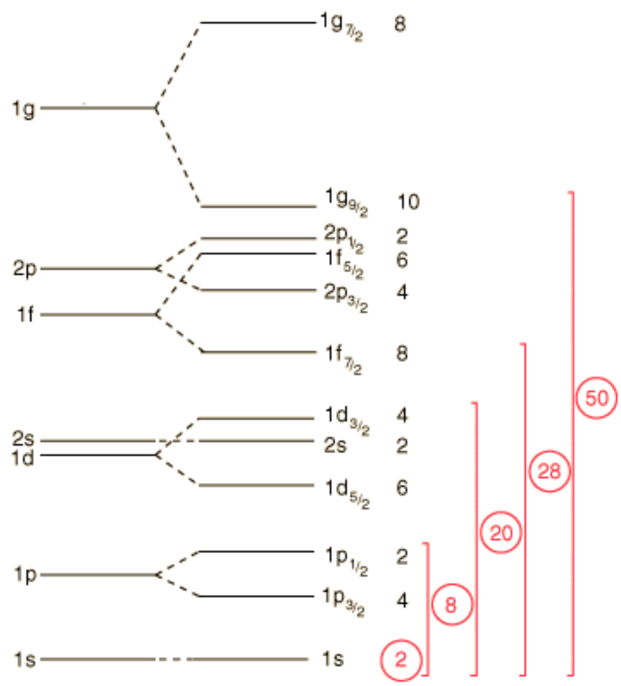
(b) For each of the following processes, state whether a neutrino, an anti-neutrino or neither will also be emitted:

i. β^- decay
ii. β^+ decay
iii. α decay
iv. γ decay
v. Decay by electron capture.

Why is decay by electron capture much more predominant in heavy atoms?

(c) Energetically, ${}^{106}_{48}$Cd could decay to ${}^{106}_{46}$Pd. Why is ${}^{106}_{48}$Cd nevertheless stable?

4. The following diagram shows the order of single-particle energy levels for the nuclear shell model.



(a) Under what assumptions does the shell model let us deduce the spins and parities of nuclear ground states? For which nuclei can we not obtain a unique prediction, even under these assumptions?

(b) Predict the spins and parities of the ground states of the following nuclei (give all possibilities if you cannot determine a unique answer):

$$ {}^{93}_{41}\text{Nb},\ {}^{33}_{16}\text{S},\ {}^{3}_{2}\text{He},\ {}^{22}_{11}\text{Na},\ {}^{96}_{42}\text{Mo},\ {}^{14}_{7}\text{N},\ {}^{71}_{32}\text{Ge} $$

(c) The ground state of ${}^{17}_{9}$F has $j^P = \frac{5}{2}^+$, and the first excited state has $j^P = \frac{1}{2}^-$. Give the full configuration for the ground state, and suggest a likely configuration for the excited state.