Introduction to nuclear and particle physics PH5211 - Problem Set 2

To be submitted to class on Tuesday 16th August 2022

Any queries contact me at libby@iitm.ac.in

Suggested references:

- Krane, Chapters 3.4, 3.5, 4.1, 4.4, 11.4 and 16.1
- Perkins, 2.10
- Martin and Shaw, Particle Physics (Wiley) Appendix B

1. Explain why the hyperfine splitting of atomic levels can be described by a perturbation of the form

$$\Delta E = A\vec{\mathbf{I}} \cdot \vec{\mathbf{J}} \ ,$$

where $\vec{\mathbf{J}}$ is the total angular momentum of the orbital electrons, $\vec{\mathbf{I}}$ is the nuclear spin and A is a constant of proportionality which varies for different levels.

Refer to Fig. 1 from lecture 5 explain why the Na ground state and second excited state are split into two and four states, respectively, by this interaction.

Estimate the constant of proportionality A for the ground, first excited and second excited states. Comment on the origin in the differing sizes of A for the differing levels.

2. Outline the evidence for nuclear forces being (a) charge independent and (b) saturating.

The deuteron ground state has the following properties:

Spin:	$I = 1$
Parity:	Even
Magnetic dipole	$\mu = 0.857\mu_N$
Electric quadrupole moment	small and positive.

What information do these quantities give about the ground state wavefunction of the deuteron?

Given also that there are no bound states of the dineutron and the diproton what can you infer about the force between two nucleons.

[μ proton = 2.793 μ_N and μ neutron = -1.913 μ_N]

3. Explain what is meant by the cross section for an interaction.

   A beam of particles passes through a solid which has n nuclei/m^3. If the total reaction cross section is σ_{t}, show that the beam intensity is given by

   $$I(x) = I_0 e^{-\, n\sigma_{\mathrm{t}} x} \ ,$$

   where x is the distance travelled in the solid, and I_0 is the incident intensity.

   The dominant interaction process for 50 keV γ rays in Pb is the photoelectric effect with cross section 2.6×10^3 barns.

   - What thickness of lead would reduce the intensity of 50 keV γ rays by three orders of magnitude?
   - What thickness of aluminium would be required to produce the same attenuation?

   You will need the following information: 1 barn $= 10^{-28}$ m^2, atomic mass of Pb is 207.21 u, atomic mass of Al is 26.29 u, $\rho(\mathrm{Al}) = 2700$ kg m^{-3}, $\rho(\mathrm{Pb}) = 11300$ kg m^{-3} and $\sigma_{\mathrm{t}}(\mathrm{Al})/\sigma_{\mathrm{t}}(\mathrm{Pb}) = 5 \times 10^{-3}$ for 50 keV γ rays.

4. A beam of neutrons with kinetic energy 0.29 eV and and an intensity of 10^5 s^{-1} traverses normally a foil of ^{235}U, thickness 10^{-1} kg m^{-2}. Any neutron-nucleus collision can have three possible results:

   (a) elastic scattering of neutrons with $\sigma_e = 20$ mb,

   (b) capture of the neutron followed by the de-excitation of the nucleus by emission of a γ ray with $\sigma_c = 70$ b, and

   (c) neutron-induced fission into two equal parts with $\sigma_f = 200$ b.

   Calculate:

   (a) the attenuation rate of the neutron beam in the foil,

   (b) the number of beam-induced fission reactions occuring per second in the foil, and

   (c) the flux of both the elastically scattered 0.23 keV neutrons and the de-excitation γ rays at a point 10 m from the foil. Assume the scattered neutrons and γ rays are isotropically distributed.