UNIVERSITY OF OSLO

Faculty of Mathematics and Natural Sciences

Exam in: FYS3510 - Subatomic physics with applications in astrophysics
Day of exam: 6. June 2016
Exam hours: 9:00 – 13:00 (4 hours)
This examination paper consists of six (6) pages in total
Appendices:
Permitted materials: *Calculator, Particle physics booklet of Particle Data Group*

Make sure that your copy of this examination paper is complete before answering.

There are seven (7) exercises in total, all with the same weight. You are asked to solve six (6) of them.

Exercise 1: Allowed, suppressed and forbidden processes

Which of the following processes are allowed and which are forbidden?

1. If allowed, draw the Feynman diagram and state which interaction is at work.
2. For allowed decays check that interaction type and lifetime are compatible.
3. If suppressed or forbidden, give the reasons. You may consider new physics scenarios if and when appropriate.

$$1.\ e^+e^- \to \nu_e\bar{\nu}_e \qquad 2.\ e^+e^- \to Z^0Z^0 \qquad 3.\ \phi \to \pi^0\pi^0$$

$$4.\ e^+e^- \to q\bar{q}\gamma\gamma \qquad 5.\ e^+e^- \to q\bar{q}gg \qquad 6.\ B_s^0 \leftrightarrow \bar{B}_s^0$$

$$7.\ {}^{82}_{34}Se \to {}^{82}_{36}Kr + 2e^- + 2\bar{\nu}_e \qquad 8.\ {}^{76}_{32}Ge \to {}^{76}_{34}Se + e^- + e^-$$

4. Assuming processes 4 and 5 are allowed, which properties or behaviors of the underlying theories can be obtained?
5. Assuming processes 7 and 8 are allowed, how would you separate them experimentally? What would be the consequences of such an observation?

Exercise 2: Charged meson decays

Consider the 2-body decay at rest of the charged pion and kaon into leptons

$$\pi^+ \to l^+\nu_l \ \ ; \ \ K^+ \to l^+\nu_l$$

1. Draw the Feynman diagrams. Calculate the momenta of the charged leptons (l=e, μ) in both decays. First conclusions?
2. Use helicity arguments to show that

$$\Gamma_{\pi,K\to l\nu} \propto \frac{m_l^2}{4}\left(1-\frac{m_l^2}{m_{\pi,K}^2}\right)^2$$

3. Discuss the following ratios and compare them to the experimental measurements. Conclude.

$$R_\pi = \frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} \ \ ; \ \ R_K = \frac{\Gamma_{K\to e\nu}}{\Gamma_{K\to\mu\nu}} \ \ ; \ \ R_\mu = \frac{\Gamma_{K\to\mu\nu}}{\Gamma_{\pi\to\mu\nu}}$$

Exercise 3: Meson decays and symmetries

1. Show explicitly that the pseudoscalar η^0 (M=548 MeV, Γ~90 keV, $J^{PC}= 0^{-+}$) meson is allowed to decay to 2 photons

$$BR(\eta^0 \to \gamma\gamma)=0.393$$

2. Show explicitly why the decay to 3 photons is forbidden

$$BR(\eta^0 \to \gamma\gamma\gamma)<1.6 \cdot 10^{-5}$$

3. Draw the Feynman diagrams of the following decays

$$B^0 \to D^- \pi^+ \ ;\ B^0 \to D^- K^+ \ ;\ B^0 \to \pi^- K^+ \ ;\ B^0 \to \pi^- \pi^+$$

4. Estimate the ratios of the two decay widths

$$\frac{\Gamma\left(B^0 \to D^- K^+\right)}{\Gamma\left(B^0 \to D^- \pi^+\right)} \ ; \ \frac{\Gamma\left(D^0 \to \pi^- K^+\right)}{\Gamma\left(D^0 \to D^- \pi^+\right)} \ ; \ \frac{\Gamma\left(D^0 \to \pi^- \pi^+\right)}{\Gamma\left(D^0 \to D^- \pi^+\right)}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347 \pm 0.00016 \\ 0.2252 \pm 0.0007 & 0.97345 \pm 0.00015 & 0.041 \pm 0.001 \\ 0.0086 \pm 0.0003 & 0.040 \pm 0.001 & 0.99915 \pm 0.00005 \end{pmatrix}$$

Exercise 4: Nuclear models

1. Explain and write down the terms contributing to the semi-empirical mass formula (SEMF).
2. Show that the mass can be written as

$$M(Z,A) = \alpha A - \beta Z + \gamma Z^2 + \frac{\delta}{A^{1/2}}$$

3. Figure 1 shows the resulting excess mass ΔM, as function of the number of protons Z, for 2 nuclei isobars, A=101 and A=106. Discuss the features of the transition sequences of the A=101 and A=106 isobars.
4. Write down one reaction (no Feynman diagrams) for each type of processes involved (four in total).

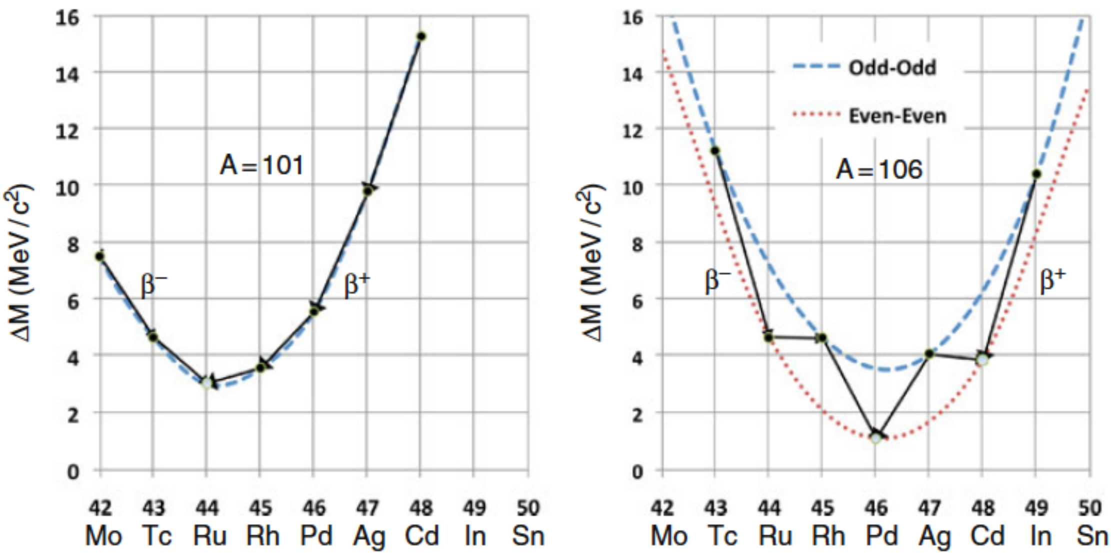

Figure 1 *Odd nuclei data (A=101, left) and Even-even and odd-odd nuclei data (A=106, right) together with the corresponding predictions of the semi-empirical mass formula.*

5. Present briefly the nuclear shell model and explain how magic numbers and other substructures of energy levels are obtained.

6. What is the spin and parity of the radioisotope $^{17}_{9}F$? Use the scheme of *Figure 2*.
7. Suggest possible configurations of the first excited state and state the one you think is the most probable. Does your answer agree with $J^P=1/2^-$, which is the first observed excited state?

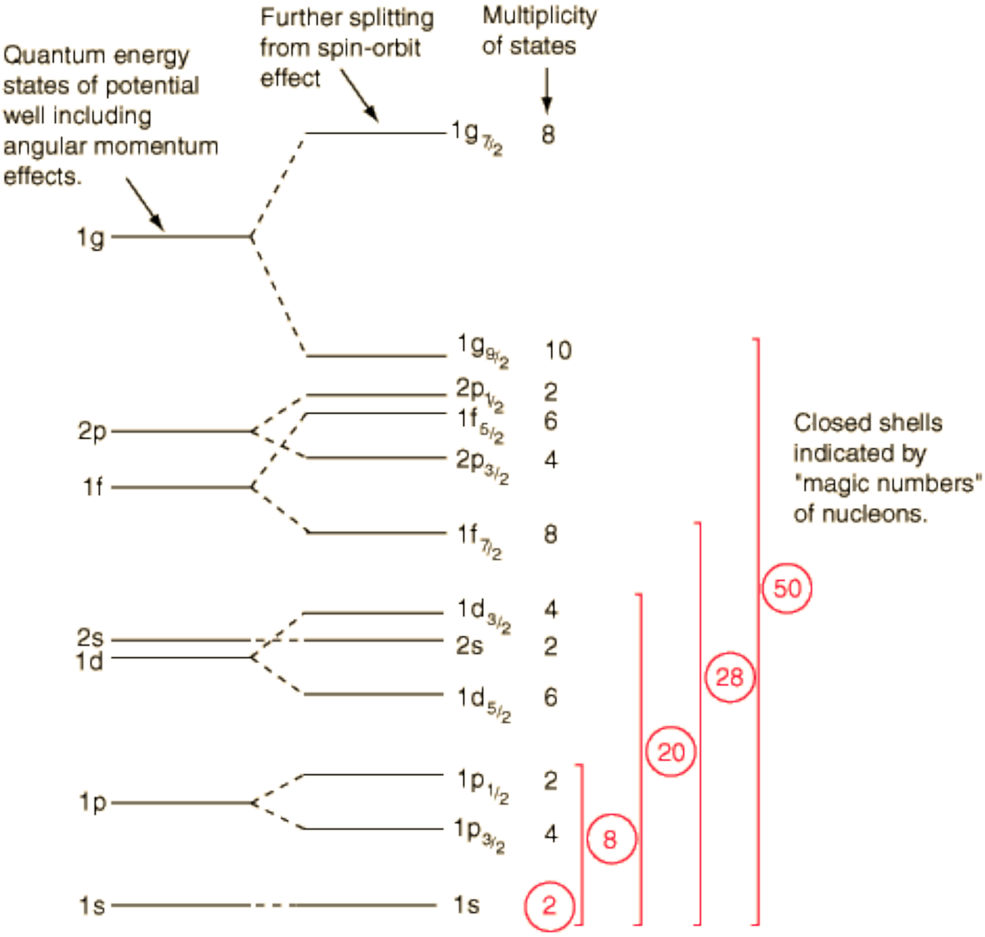

Figure 2 *Energy levels of nuclei as predicted by the Shell model.*

Exercise 5: Lepton-nucleon and electron-nucleus scattering

1. Explain how electron-nucleus scattering allowed extracting important information about the structure of nuclei. You may make use of *Figure 3* to consolidate your arguments.
2. What is deep inelastic scattering (DIS)? Draw the Feynman diagram(s) for muon and neutrino scattering.
3. How did it lead to the discovery of the structure of nucleons in terms of elementary partons? How were these partons identified with quarks and gluons?

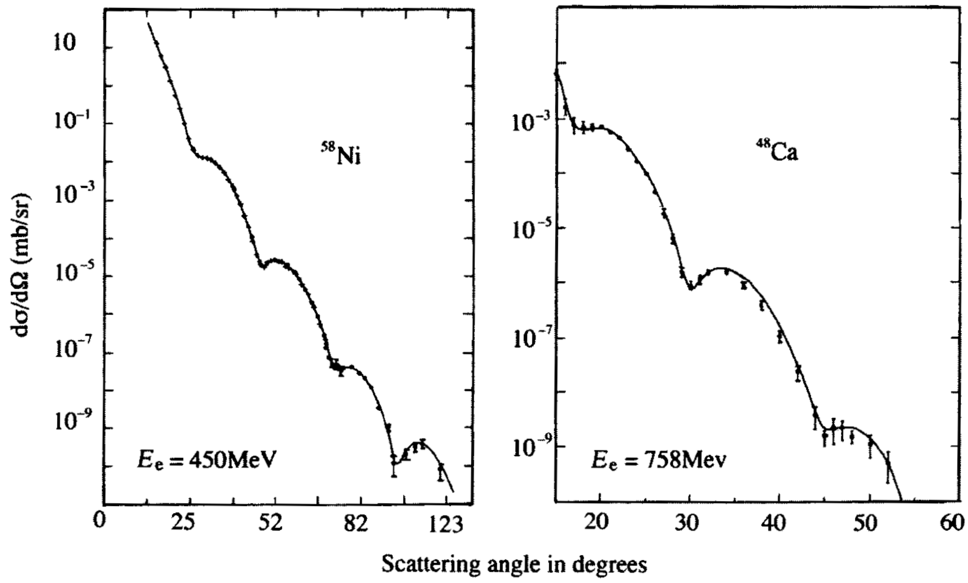

Figure 3 *Differential cross-section for electron nucleus scattering as a function of the scattering angle.*

Exercise 6: e^+e^- resonances

1. How is the J/ψ charmonium state produced in e^+e^- and ep collisions? Give the Feynman diagrams?
2. How does the J/ψ decay? Explain why the J/ψ resonance is much narrower (Γ~90 keV) than normal hadrons (Γ ~10-100 MeV).
3. How is the Z boson produced in proton-proton collisions?
4. List all possible decays of the Z boson.
5. Explain how the experiments at the Large Electron Positron (LEP-I) e^+e^- collider (center of mass energy √s~91±3 GeV) constrained the number of light neutrinos. How light?

$$e^+e^- \to Z \to f\,\bar{f}$$

$$\sigma(s) = \frac{12\pi}{m_Z^2} s \frac{\Gamma_{ee}\Gamma_{ff}}{\left(s - M_Z^2\right)^2 + s^2\Gamma_Z^2 / m_Z^2}$$

$$s = m_Z^2 \Rightarrow \sigma^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

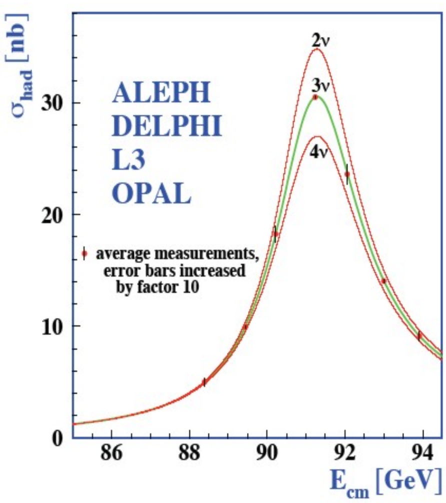

Figure 4

Exercise 7: Isospin symmetry

1. What is strong isospin, I? What is the behavior of strong and electromagnetic interactions w.r.t isospin? Give examples of isospin multiplets I=1/2, I=1, I=3/2.
2. Make use of *Figure 5* to evaluate the ratio between the cross-sections of the following reactions at the same energy, in terms of the isospin amplitudes A_0, A_1 and A_2.

$$(1)\ K^- p \rightarrow \pi^+\Sigma^- \quad (2)\ K^- p \rightarrow \pi^0\Sigma^0 \quad (3)\ K^- p \rightarrow \pi^-\Sigma^+$$

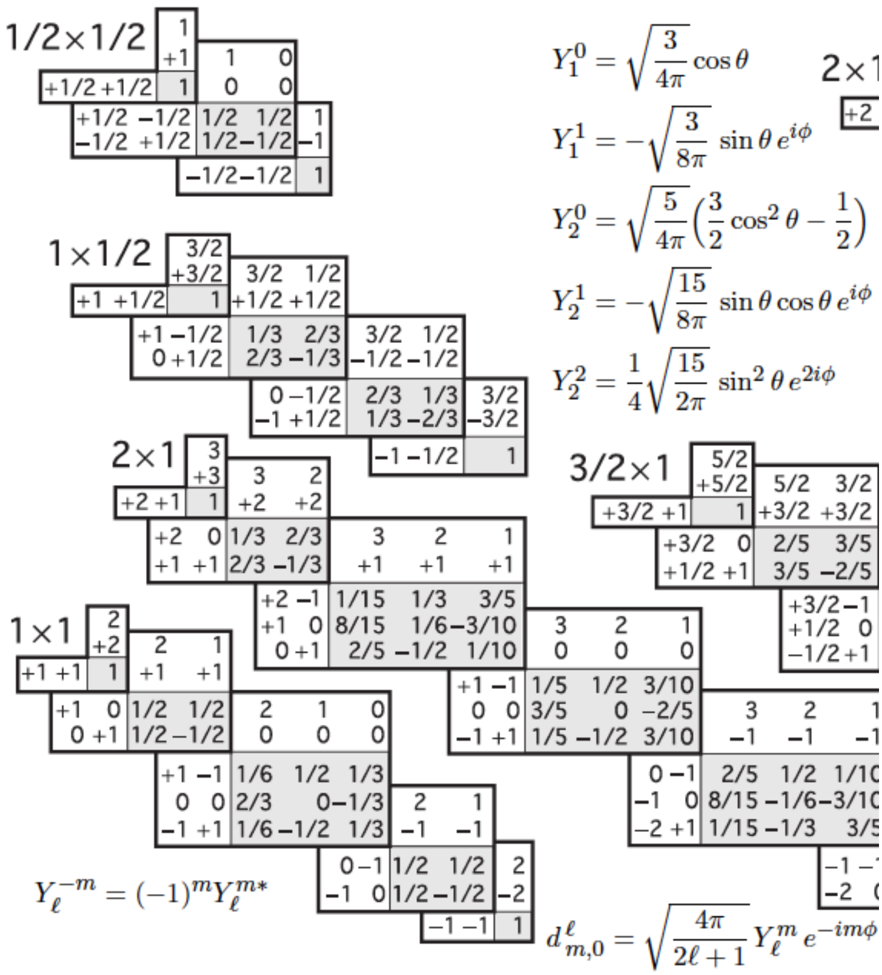

Figure 5 *Clebsh Gordon coefficients. Note that for each cell of the table there is an implied square root so that -1/2 should be read as -√(1/2), etc.*