UNIVERSITY OF OSLO

Faculty of Mathematics and Natural Sciences

Exam in FYS3500 - Introduction to nuclear and particle physics
Day of exam: 6 June, 2019
Exam hours: 14:30-18:30

This examination paper consists of 8 page(s).
Appendices: None
Permitted materials: Chart of the nuclides, calculator

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

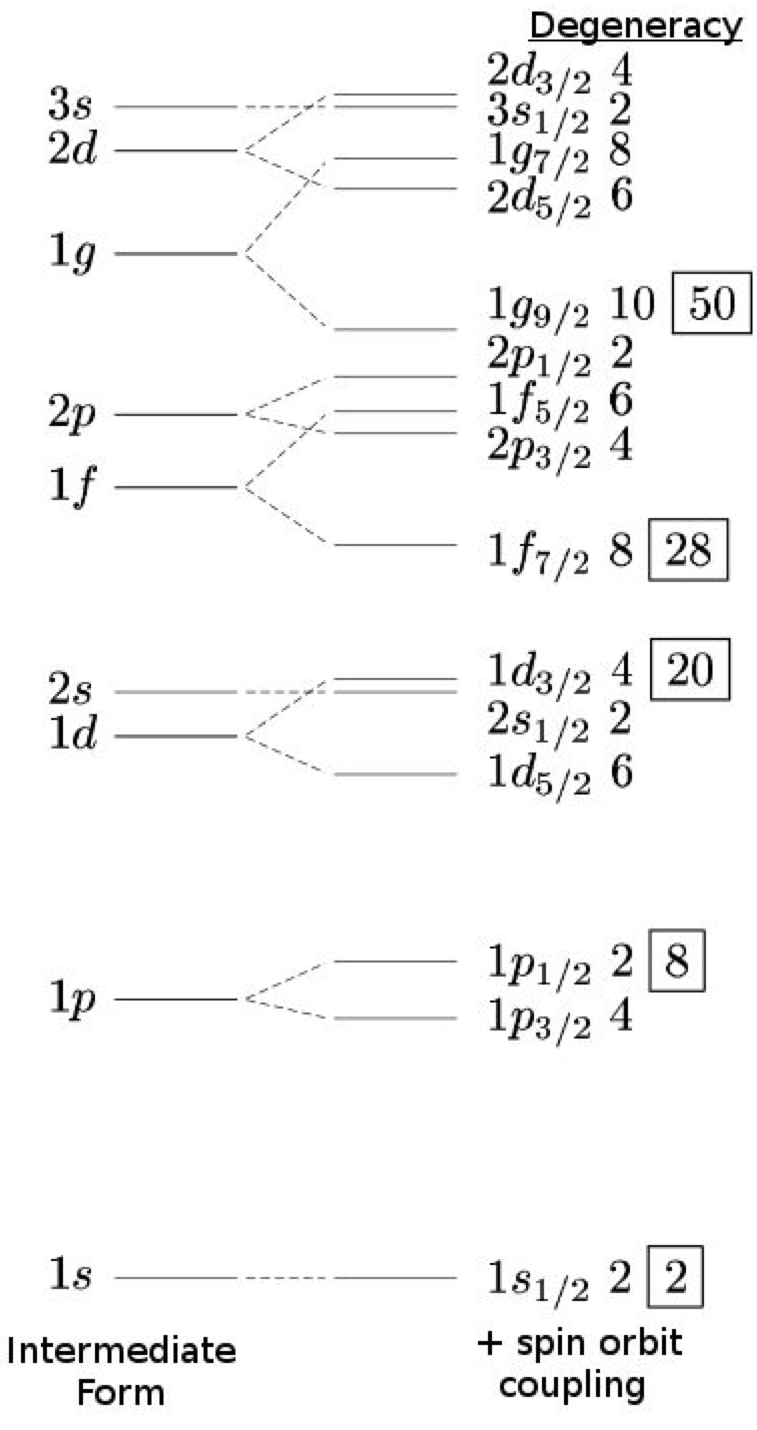
100 points total

Useful constants:

$c = 3 \cdot 10^8$ m/s
$\hbar c = 197$ MeV-F
$G_F = 1.166 \cdot 10^{-5}$ GeV^{-2}

Particle	Quark composition	Mass (MeV/c^2)
π^+	$u\bar{d}$	140
π^0	$u\bar{u},\ d\bar{d}$	135
K^+	$u\bar{s}$	494
K^0	$d\bar{s}$	498
n	udd	940
p	uud	938
Λ^0	uds	1116

Shell Model - Energy Levels



1. Concepts in particle physics (7 points)

Associate the following list of concepts with the symbols or formulae below:

a) Flavor-changing neutral current
b) Isospin symmetry
c) Parity violation
d) Color confinement
e) Electroweak unification
f) Lepton universality
g) Lepton-quark symmetry

1) Σ^+ (1189 MeV) = uus, Σ^0 (1193 MeV) = uds, Σ^- (1197 MeV) = dds
2) $\Gamma(W^+ \to e^+\nu_e) \simeq \Gamma(W^+ \to \tau^+\nu_\tau)$
3) $e/(2\sqrt{2\varepsilon_0}) = g_W sin(\theta_W) = g_Z cos(\theta_W)$
4) $\Gamma_{\mu^+ \to e^+\nu_e\overline{\nu_\tau}}(cos\theta) \neq \Gamma_{\mu^+ \to e^+\nu_e\overline{\nu_\tau}}(cos(\pi - \theta))$
5) $\Gamma(W^+ \to u\overline{d'}) = 3\,\Gamma(W^+ \to e^+\nu_e)$
6) $B_s^0(\overline{b}s) \to \mu^+\mu^-$
7) $I_3^c = Y^c = 0$

2. Multiple choice (3 points)

1. The half-life $t_{1/2}$ for α-decay for a chain of isotopes
   a. increases with Q-value.
   b. decreases with Q-value.
   c. is independent of the Q-value.
2. The half-life $t_{1/2}$ for α-decay for a chain of isotopes
   a. decreases with increasing deformation.
   b. increases with increasing deformation.
   c. is independent of deformation.
3. With increased excitation energy of the nucleus we find in general states with shorter half-life and
   a. smaller width Γ.
   b. larger width.
   c. the same width.

3. Nuclear forces (4 points)

a) The nuclear force is described as "charge independent". Why don't we observe a bound system of two protons or two neutrons in nature?

b) What is the typical range of the nuclear force and why is it so much shorter than for example the electromagnetic force?

4. Nuclear binding energy (16 points)

a) Make a sketch of the binding energy per nucleon versus mass number A. Where is the maximum?

b) Write down the binding energy formula and explain the different terms.

c) From which term can we learn about the range of the nuclear force? Explain briefly.

d) The stable light nuclei have roughly the same number of neutrons N and protons Z. For heavier nuclei there is a deviation from this N=Z line. In which direction is the deviation and which term is responsible? Explain briefly.

e) Why are ^{233}U, ^{235}U and ^{239}Pu fissionable with high probability by thermal neutrons, while ^{232}Th and ^{238}U are not? Hint: Think about the δ -term.

f) The fission fragments of fissile nuclei are not distributed symmetrically in mass, why?

5. Shell model (6 points)

a) Find and explain ground state spin and parity of ^{43}Sc.

a) Consider ^{48}Ca (N=28, Z=20). If we now take one neutron from the level $1f_{7/2}$ and promote it to the level $2p_{3/2}$, we would have an excited state. What are the possible values for the spin and parity of this excited configuration?

6. Gamma decay (10p)

a. For decay from states in the nucleus with the initial state J_i^π to the final state J_f^π, what are the possible γ decays (E1, M1 etc). If more than one are possible which is the most probable?
   i. $1^+ \to 1^+$
   ii. $9/2^- \to 3/2^+$
   iii. $2^+ \to 2^-$
   iv. $0^+ \to 0^+$
b. In an experiment you observe three γ -rays with following energies and multipolarities:
   i. 100 keV, E2
   ii. 200 keV, M1
   iii. 300 keV, E1

   No higher energy gamma-rays were observed. *Construct the most probable level scheme(s), including spin assignment of the levels.* Hint: There are (at least) two possible solutions.
c. As hinted upon, there are several possible solutions. Discuss *briefly* a possibility to distinguish between them (i.e. what additional measurement would be needed and why).

7. Radioactive decay (12 points)

A nucleus A is unstable and decays with the decay constant λ_A to a another unstable nucleus B. This decays further to the nucleus C with the decay constant λ_B. This is usually written as $A \to B \to C$.

a) *Derive* the decay law, i.e. the number of particles of A, $N_A(t)$, at a given time t, from the number of particles A at time zero, $N_{A,0}$.
b) *Prove* that the number of particles B at time t is given by
   $N_B(t) = \frac{N_{A,0}\lambda_A}{\lambda_B - \lambda_A}(e^{-\lambda_A t} - e^{-\lambda_B t})$.
c) Suppose there was a lump of $^{76}_{32}Ge$ (~1 mol, 6×10^{23} atoms) just after the big bang $(13.8 \times 10^9$ years ago). The half-life of $^{76}_{32}Ge$, which decays mainly by double-beta decay, is 1.78×10^{21} years. How many decays are there per week today?
d) Why are the shapes of the energy spectra for β^+ and β^- in nuclear decays different?

8. Medical application (4 points)

a) What is the advantage of proton therapy versus conventional radiation therapy with electrons or X-rays?
b) Sketch the proton radiation dose as a function of depth in the body.

9. Quark-gluon plasma (4 points)
Explain why the J/Ψ ($c\bar{c}$) and $\Upsilon(b\bar{b})$ states are expected to be suppressed in the quark-gluon plasma that is formed during high-energy collisions between heavy ions. Also, tell what happens to the bottom and charmed quarks when a J/Ψ or Υ meson is "suppressed", i.e., what sorts of charm and bottom particles emerge from the plasma.

10. Hadrons and quarks (8 points)
Consider the decay sequence $\Lambda_b^0(udb) \to K^-(\bar{u}s)\, P_c^+$ followed by the decay $P_c^+ \to p\, J/\Psi$, where the P_c^+ is an exotic hadron consisting of $uudc\bar{c}$.

a) As you solve part (b), identify which interaction types are most likely to mediate the two decays (explain your answers).
b) Draw the quark diagrams for the decay sequence.
c) Describe qualitatively how to determine experimentally whether the P_c^+ exists as a bound state in Λ_b^0 decays.

11. The Higgs boson (8 points)
The decay rate of the Higgs boson H to fermion-antifermion pairs $f\bar{f}$ is given by $\Gamma(H \to f\bar{f}) = (N_c)\alpha_W(m_f^2/m_W^2)m_H$.

a) What is the factor N_c for quarks and leptons, i.e. what does it account for and how big is it?
b) Predict the ratios of branching fractions (symbols only) $B(H \to b\bar{b})\ :\ B(H \to c\bar{c})\ :\ B(H \to \tau^+\tau^-)$.
c) Describe how the Higgs boson can decay to pairs of massless photons ($H \to \gamma\gamma$) or gluons ($H \to gg$), i.e. suggest 1-2 likely Feynman diagrams for each.

12. The Standard Model (8 points)

a) How many continuous variable parameters are needed to describe the entire Standard Model of fundamental particles and interactions? Explain your reasoning/accounting for the various contributions to the total.
b) How many of these parameters are given by pure theory and how many need to be determined by experiment?

13. Relativistic kinematics (10 points)

A beam of negatively charged pions (π^-) hits protons at rest. What is the minimum energy of the pion beam (or the minimum momentum if you prefer) needed to produce a Λ^0 ? Hint: Describe what type of interaction this is most likely to be (let's say the cross-section is very large) and think about how to insure that the relevant quantum numbers are conserved. A correct symbolic answer will receive full credit, but it could be a good idea to plug in some numbers and check if your formula gives sensible results.