**FYS 3500 - Midterm Exam Spring 2024 (home exam)**

Deadline to hand it in is Friday, March 22, 2024, 23:59

The delivery will be in Canvas.

The grading is Pass/Fail.

Ask for clarifications in https://astro-discourse.uio.no/c/fys3500-24v.

**Useful resources:**

- Books presented in the lecture/problem sessions
- Chart of nuclides on http://www.nndc.bnl.gov/
  e.g. masses, lifetimes, energy levels, decay schemes, …
- Also: Livechart – Table of Nuclides:

  https://www.nndc.bnl.gov/nudat3/

- Particle physics: Lifetimes, decay widths, ...
  http://pdg.lbl.gov

Please cite external references where used.

**Regarding collaboration:**

You are allowed and **encouraged** to collaborate when working out the exercises**.** You can also submit together with a maximum of 3 people per submission (you should be able to register your team in Canvas - let us know if that doesn't work).

Good luck and have fun!

1. **Cross sections**

a) Suppose we observe 2.25 million events from a process with a (well-understood) cross section of 1 pb and a detection efficiency of 75%. What is the integrated luminosity of this dataset? We observe 1850 events while searching for a rarer process in the same dataset with 1% efficiency and a predicted background of 1000 events. What is the cross section of this rare process?

c) What is the (approximate) ratio of cross sections for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ and $e^+e^- \rightarrow q\bar{q}g$ (a very simple formula, nothing numerical expected)? Draw 2 relevant Feynman diagrams and use some of their important features to justify your answer.

2. **Nuclear properties and force**

a) What can we learn about the nucleus from the past nuclear scattering experiments? Explain briefly.
b) Is nuclear radius a definitive property of the nucleus? Explain briefly.
c) Explain up to three properties of nuclear force by giving examples on experimental findings, if applicable.

3. **Nuclear binding energy**

a) Using the semi-empirical binding energy formula, explain why the N/Z ratio of stable nuclei is approx. 1 for light nuclei and then increases with A.
b) Explain briefly the three components of the semi-empirical binding energy formula which are based on the liquid drop model.
c) Rank these nuclei from highest to lowest neutron separation energy Sn: $^{118}$Sn, $^{16}$O, or $^{119}$Sn? Explain your reasoning, not just look up the $S_n$.
d) Sketch the mass as a function of Z for the A=136 isobars (mass parabola) and explain how the beta decay flows between nuclei with A=136. Also make a sketch for a case where A is an odd number, for example A=135, explain the difference from the even A case.

**4. Nuclear Shell model**

a) What experimental evidence do we have for the nuclear shell model? Describe two different observations.
b) What do we mean when the nuclear potential is central within the independent particle model? Why do we use a central potential instead of a more realistic one, for example two-body nucleon-nucleon potential? Explain briefly.
c) Choose a form of nuclear potential as a function of radial distance and sketch it in the framework of the independent particle model. Explain your choice in the form of the potential. Could one also add repulsive components? If yes, what components can they be?
d) Using the nuclear shell model, find and explain the nucleon configuration of the 15N ground state and first excited state. Also determine the spin and parity of these states. https://www.nndc.bnl.gov/nudat3/getdatasetClassic.jsp?nucleus=15N&unc=nds
e) Using the experimentally determined second and third excited states from the link above, are you able to identify their nucleon configurations?

**5. Relativistic B-meson pairs at SuperKEKB**

At SuperKEKB 7 GeV electrons collide head-on with 4 GeV positrons. To simplify your calculations, approximate the mass of the electron to be 0.

a) What is the center of mass energy ($\sqrt{s}$) of the colliding $e^+e^-$ pair?

b) What sort of B-meson pairs can be created at this $\sqrt{s}$? (It's enough to identify one pair, but there are two.)

c) Assuming the two B-mesons equally share the energy and momentum of the initial state in the laboratory frame, what are their relativistic $\beta$ and $\gamma$ (formulas AND numerical results)?

d) How far, on the average, do these B-mesons travel before decaying (formula AND numerical result).

**6. Neutrino oscillations**

We wish to study neutrino oscillations. Assume that we can ignore mixing between the first two generations of neutrinos and the third. Let's say we want to test the hypothesis that $\Delta m_{21}^2 = 7.5 \cdot 10^{-5}$ (eV/c$^2$)$^2$ and $tan^2\theta_{12} = 0.444$ with a 100 MeV beam of $\nu_\mu$.

a) At what distance (in m or km) would we find the first maximum of intensity of $\nu_e$?

b) What would the relative intensities of $\nu_e$ and $\nu_\mu$ be at this distance?

**7. Quantum numbers**

a) What is the $J^{PC}$ of a ${}^1S_0$ bound state of $b\bar{b}$? Is $J^{PC}$ the same or different for a ${}^1S_0$ bound state of $e^+e^-$?

b) Can the ${}^1S_0$ bound state of $b\bar{b}$ be produced directly in $e^+e^-$ collisions (justify your answer)?

c) Which of the $\pi^+, \pi^0, \pi^-$ can or can't be eigenstates of C-parity? Explain why.

**8. Allowed, suppressed and forbidden processes**

(For **scattering** processes assume there is enough energy in the initial state to produce the final state.)

a) $\nu_e e^- \rightarrow \nu_\mu \mu^-$

b) $\Lambda^0 \rightarrow p\pi^-$

c) $\mu^+\mu^- \rightarrow t\bar{t}$

d) $\bar{p} \rightarrow n e^- \bar{\nu}_e$

For each process (a)-(d):
Is the process allowed, suppressed, or forbidden? Explain your reasoning. You may consider new physics scenarios if and when appropriate. If allowed, draw the (dominant) Feynman diagram(s) and state which interaction(s) is (are) at work. For allowed *decays* check that the interaction type and lifetime (or half-life) are compatible.