LAST (Family) NAME: ____

FIRST (Given) NAME: ____

STUDENT NUMBER: ____________________________

UNIVERSITY OF TORONTO
Faculty of Arts and Science
APRIL 2022 EXAMINATIONS
PHY 357 H1S
Particle and Nuclear Physics
Duration: 3 hours

Aids allowed: Non-Programmable scientific calculator, without text storage
One, personally prepared (not mechanically photo-copied/photo-reduced), aid-sheet
(materials can appear on both sides of a single 8.5" x 11" sheet).

Exam Reminders:

- Fill out your name and student number at the top of this page and on any examination booklets you wish to hand in.
- Do not begin writing the actual exam until the announcements have ended and the Exam Facilitator has started the exam.
- As a student, you help create a fair and inclusive writing environment. If you possess an unauthorized aid during an exam, you may be charged with an academic offence.
- Turn off and place all cell phones, smart watches, electronic devices, and unauthorized study materials in your bag under your desk. If it is left in your pocket, it may be an academic offence.
- When you are done your exam, raise your hand for someone to come and collect your exam. Do not collect your bag and jacket before your exam is handed in.
- If you are feeling ill and unable to finish your exam, please bring it to the attention of an Exam Facilitator so it can be recorded before leaving the exam hall.
- In the event of a fire alarm, do not check your cell phone when escorted outside.

Special Instructions:

There are **six** questions on this exam. You must answer **five** of them. Each question is worth **20 %** of the full examination grade. If you answer more than five please indicate which five you want to count, otherwise only the first five attempted will be graded and included in your final score.

Partial credit will be given for partially correct answers, so show any intermediate calculations that you do and write down, **in a clear fashion**, any relevant assumptions you are making along the way.

There are two pages of background material, not all of which you'll need to answer the questions, that are found on pages two and three of this paper. The questions start on page **four** and continue to page **six**.

Students must hand in all examination materials at the end.

1. (a) Explain the meaning of the following terms used in the classification of particles:
   i. hadron;
   ii. lepton;
   iii. boson;
   iv. fermion;
   v. baryon;
   vi. meson.

   (b) Which of the terms from the list above applies to each of the following particles:
   i. $\bar{s}$-quark;
   ii. Z^0;
   iii. τ^-;
   iv. D^+;
   v. Ξ^0;
   vi. H^0;
   vii. n.

   In some cases more than one term from part a) may apply. To get full credit include all that apply.

2. CERN's Large Electron Positron collider (LEP) had a diameter of 8 km and produced beams of energy 45 GeV. Each beam consisted of 12 bunches, and each bunch contained 3×10^{11} particles (electrons or positrons, depending on the beam). The bunches had a cross-sectional area of 0.02 mm^2.

   (a) What was the luminosity of this machine in units of cm^{-2} s^{-1}?

   (b) If the cross-section to produce a Z-boson at a centre-of-mass energy of 90 GeV is 1 nb, how many Z bosons were produced per second, when the LEP collider was running?

   There were four experiments located around the LEP ring that were designed to study the decay of the resulting Z (and W bosons) that LEP produced. The LEP experiments used similar detector strategies to ATLAS, as discussed in class. What would the experimental signatures have been for the following decays:

   (c) $Z \to b\bar{b}$;

   (d) $W \to e\nu$;

   (e) $W \to \mu\nu$.

   To get full credit you must list at least two detector signatures (effects that can be exploited by a detector system we discussed in class) for each of these decays.

3. For each of the processes listed below, clearly state what force mediates the interaction and draw *all* of the lowest-order Feynman diagrams (unless otherwise stated).

   (a) $e^+e^- \to H^0 + Z^0$

   (b) $e^+e^- \to W^+W^-$

   (c) $e^+e^- \to B^+B^-\pi^0$ (for this one you only need to draw one of the lowest order diagrams)

   For the following three processes, state what values of orbital angular momentum are allowed between the final state particles.

   (d) $\Delta^{++} \to p + \pi^+$

   (e) $\Sigma^0 \to \Lambda + \gamma$

   (f) $D^+ \to K^+ + K_S^0$

4. Examine the following processes and state for each one whether it represents a possible reaction, or if it is impossible according to the Standard Model we've discussed in PHY357. If the interaction is possible, state which interaction mediates it, for example strong, electromagnetic or weak. If the reaction is impossible, cite a conservation law that prevents it from occurring. If the process is a weak decay involving quarks, state whether it is Cabbibo-favoured, or Cabbibo-suppressed. Only consider lowest order processes.

$\pi^0 \to \gamma + \gamma$	$\Xi^- \to \Lambda^0 + \pi^-$	$n \to p + e^- + \bar{\nu}_e$
$\Lambda^0 \to \Sigma^0 + \pi^0$	$D^+ \to K^+ + \pi^0$	$\pi^+ + n \to \pi^- + p$
$\bar{\nu}_e + p \to e^+ + \pi^0$	$\Delta^{++} \to p + \pi^+$	$p + \bar{p} \to B^+ + B^-$
$\tau^- \to e^- + \bar{\nu}_e$	$n + \bar{n} \to \pi^+ + \pi^- + \pi^0$	$\Sigma^- \to n + \pi^-$

   Partial credit will be given for listing all the quantum numbers that **are** conserved even in cases where you might miss the one that prevents a reaction from proceeding. So provide some notes on your thought process as you try to work out whether the reactions are allowed.

5. Draw a Feynman diagram for each of the following decays.

$$\Omega^- \rightarrow \Xi^- + \pi^0 \qquad B^- \rightarrow D^0 + \pi^-$$
$$\rho^+ \rightarrow \pi^+ + \pi^0 \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\Delta^0 \rightarrow p + \pi^- \qquad K^+ \rightarrow \pi^+ + \pi^0$$
$$\Lambda_b \rightarrow \Lambda_c^+ + \mu^- + \bar{\nu}_\mu \qquad \tau^- \rightarrow \pi^- + \nu_\tau$$

For those involving hadrons make sure you show all the quarks that are involved.

6. The semi-empirical binding energy formula is based on the idea that the nucleus behaves like a liquid drop, with corrections for the Coulomb energy and Fermi levels in the nuclear potential. It takes the form:

$$\text{Binding Energy} = -a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_A(\frac{A}{2} - Z)^2 \pm a_F A^{-3/4}$$

   (a) Briefly explain (two or three sentences **for each term**, so 10-15 sentences in total!) the physical origin for each of the **five** terms in the binding energy expression above.
   (b) Sketch the rough shape of the first three contributions (a_V, a_S and a_C Binding Energy curve (B) (not binding energy per nucleon).
   (c) Also sketch the Binding Energy/nucleon curve (B/A) for the sum of all terms, that we looked at numerous times in class.
   (d) Explain what the shape of this curve tell us about which nuclei are most stable, which participate in fusion reactions and which participate in fission reactions?
   (e) Compute the total binding energy for ${}^{8}_{4}Be$, and ${}^{56}_{26}Fe$. To do this use: $a_V = 15.8$ MeV, $a_S = 17.8$ MeV, $a_C = 0.71$ MeV, $a_A = 23.8$ MeV and $a_F = 12$ MeV.

End of examination
Total pages: 6