Your name sticker with **exam code**

1. The exam will last from 12:00pm to 3:00pm. Use a #2 pencil to make entries on the answer sheet. Enter the following id information now, before the exam starts.

2. In the section labelled NAME, enter your last name, then fill in the empty circle for a blank, then enter your first name, another blank, and finally your middle initial.

3. Under STUDENT # enter your 9-digit Student ID Number. Under COURSE enter 273. Under CODE enter the exam code given above.

4. During the exam, you may use pencils, a calculator, and **ONE** 8½" × 11" sheet of paper with formulas and notes.

5. There are 16 multiple-choice questions on the exam. For each question, mark only one answer on the answer sheet. There is no subtraction of points for an incorrect answer, so even if you cannot work out the answer to a question, you should make an educated guess. At the end of the exam, hand in both the question and the answer sheets. The question paper will be returned to you after the exams are graded.

6. Useful numerical constants are given on the next two pages. Before starting the exam, make sure that your copy contains the pages of constants and all 16 questions. Bring your exam to the proctor if this is not the case.
Elementary charge \( e = 1.6 \times 10^{-19} \ C \)

1 electron volt (eV) = 1.6 \times 10^{-19} J

Speed of light \( c = 3 \times 10^8 \ m/s \)

Planck’s constant \( h = 6.63 \times 10^{-34} \ J \cdot s = 1240 \ nm \cdot eV/c \)

\( \hbar = h/2\pi \)

Avogadro’s number = 6.02 \times 10^{23} \ molecules/mole

Electron mass = 9.11 \times 10^{-31} \ kg = 0.511 \ MeV/c^2 = 0.000549 \ u

Proton mass = 1.673 \times 10^{-27} \ kg = 938.3 \ MeV/c^2

Neutron mass = 1.675 \times 10^{-27} \ kg = 939.6 \ MeV/c^2 = 1.008665 \ u

Hydrogen atom mass = 1.007825 \ u

Atomic mass unit 1 u = 931.5 \ MeV/c^2

Fine structure constant \( \alpha = 1/137 \)

Hubble constant \( H = 0.0215 \ m/s/light \ year = 70 \ km/s/Mpc \)

1 parsec (pc) = 3.26 light years

Powers of ten:

<table>
<thead>
<tr>
<th>femto (f)</th>
<th>pico (p)</th>
<th>nano (n)</th>
<th>micro (µ)</th>
<th>milli (m)</th>
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<td>10^{-12}</td>
<td>10^{-9}</td>
<td>10^{-6}</td>
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<table>
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<th>centi (c)</th>
<th>kilo (k)</th>
<th>Mega (M)</th>
<th>Giga (G)</th>
<th>Tera (T)</th>
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<td>10^6</td>
<td>10^9</td>
<td>10^{12}</td>
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</tbody>
</table>

THE LEPTONS (all spin \( \frac{1}{2} \))

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Common decays</th>
<th>( L_e )</th>
<th>( L_\mu )</th>
<th>( L_\tau )</th>
<th>Antiparticle</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- ) (0.511)</td>
<td>Stable</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>e^+</td>
</tr>
<tr>
<td>( \nu_e ) (0?)</td>
<td>Stable (?)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( \nu_e )</td>
</tr>
<tr>
<td>( \mu^- ) (106)</td>
<td>( e^-\nu_\mu )</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>( \mu^+ )</td>
</tr>
<tr>
<td>( \nu_\mu ) (0?)</td>
<td>Stable (?)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>( \nu_\mu )</td>
</tr>
<tr>
<td>( \tau^- ) (1777)</td>
<td>( \pi^-\pi^0\nu_\tau, e^-\nu_e\nu_\tau, \mu^-\nu_\mu\nu_\tau )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>( \tau^+ )</td>
</tr>
<tr>
<td>( \nu_\tau ) (0?)</td>
<td>Stable (?)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>( \nu_\tau )</td>
</tr>
</tbody>
</table>

THE QUARKS (all spin \( \frac{1}{2} \))

Baryon number = +1/3 for all quarks, and −1/3 for all antiquarks

S = strangeness, C = charm, B = bottomness, T = topness

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Charge</th>
<th>S</th>
<th>C</th>
<th>B</th>
<th>T</th>
<th>Antiparticle</th>
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</thead>
<tbody>
<tr>
<td>Down</td>
<td>( d )</td>
<td>(-1/3)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( \bar{d} )</td>
</tr>
<tr>
<td>Up</td>
<td>( u )</td>
<td>(+2/3)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( \bar{u} )</td>
</tr>
<tr>
<td>Strange</td>
<td>( s )</td>
<td>(-1/3)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( \bar{s} )</td>
</tr>
<tr>
<td>Charm</td>
<td>( c )</td>
<td>(+2/3)</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>( \bar{c} )</td>
</tr>
<tr>
<td>Bottom</td>
<td>( b )</td>
<td>(-1/3)</td>
<td>0</td>
<td>0</td>
<td>−1</td>
<td>0</td>
<td>( \bar{b} )</td>
</tr>
<tr>
<td>Top</td>
<td>( t )</td>
<td>(+2/3)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>( \bar{t} )</td>
</tr>
</tbody>
</table>
HADRONS (strongly interacting particles)

Baryon number = +1 for baryons, −1 for antibaryons, 0 for all others
S = strangeness, C = charm, B = bottomness

SOME BARYONS (all are fermions: half-integer spin)

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Common decays</th>
<th>S</th>
<th>C</th>
<th>B</th>
<th>Antiparticle</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (938)</td>
<td>Stable</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>p</td>
</tr>
<tr>
<td>n (940)</td>
<td>$p e^- \bar{\nu}_e$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>n</td>
</tr>
<tr>
<td>$\Lambda$ (1116)</td>
<td>$p \pi^-$, $n \pi^0$</td>
<td>−1</td>
<td>0</td>
<td>0</td>
<td>$\Lambda$</td>
</tr>
<tr>
<td>$\Sigma^+$ (1189)</td>
<td>$p \pi^0$, $n \pi^+$</td>
<td>−1</td>
<td>0</td>
<td>0</td>
<td>$\Sigma$</td>
</tr>
<tr>
<td>$\Sigma^0$ (1193)</td>
<td>$\Lambda\gamma$</td>
<td>−1</td>
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<td>0</td>
<td>$\Sigma^0$</td>
</tr>
<tr>
<td>$\Sigma^-$ (1197)</td>
<td>$n\pi^-$</td>
<td>−1</td>
<td>0</td>
<td>0</td>
<td>$\Sigma^-$</td>
</tr>
<tr>
<td>$\Xi^0$ (1315)</td>
<td>$\Lambda\pi^0$</td>
<td>−2</td>
<td>0</td>
<td>0</td>
<td>$\Xi^0$</td>
</tr>
<tr>
<td>$\Xi^-$ (1321)</td>
<td>$\Lambda\pi^-$</td>
<td>−2</td>
<td>0</td>
<td>0</td>
<td>$\Xi^-$</td>
</tr>
<tr>
<td>$\Omega^-$ (1672)</td>
<td>$\Lambda K^-$, $\Xi^0\pi^-$</td>
<td>−3</td>
<td>0</td>
<td>0</td>
<td>$\Omega^-$</td>
</tr>
<tr>
<td>$\Lambda_c^+$ (2285)</td>
<td>Various</td>
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<td>+1</td>
<td>0</td>
<td>$\Lambda_c^-$</td>
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<tr>
<td>$\Lambda_b^+$ (5624)</td>
<td>Various</td>
<td>0</td>
<td>0</td>
<td>−1</td>
<td>$\Lambda_b^-$</td>
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</table>

SOME MESONS (all are bosons: integer spin)

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Common decays</th>
<th>S</th>
<th>C</th>
<th>B</th>
<th>Antiparticle</th>
</tr>
</thead>
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<tr>
<td>$\pi^+$ (140)</td>
<td>$\mu^+\nu_\mu$</td>
<td>0</td>
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<td>$\pi^-$</td>
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<tr>
<td>$\pi^0$ (135)</td>
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<td>0</td>
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<tr>
<td>$\eta^0$ (547)</td>
<td>$2\gamma$, $3\pi^0$</td>
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<td>0</td>
<td>0</td>
<td>Self</td>
</tr>
<tr>
<td>$K^+$ (494)</td>
<td>$\mu^+\nu_\mu$, $\pi^-\pi^0$</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>$K^-$</td>
</tr>
<tr>
<td>$K^0$ (498)</td>
<td>$2\pi$, $3\pi$, $\ldots$</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>$K^0$</td>
</tr>
<tr>
<td>$D^+$ (1869)</td>
<td>$K^\pm$, $D^0$, $\ldots$</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>$D^-$</td>
</tr>
<tr>
<td>$D^0$ (1865)</td>
<td>$K^\pm$, $D^0$, $\ldots$</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>$D^0$</td>
</tr>
<tr>
<td>$D_s^+$ (1969)</td>
<td>$K^\pm$, $D^0$, $\ldots$</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
<td>$D_s^-$</td>
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<tr>
<td>$J/\psi$ (3097)</td>
<td>Various</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Self</td>
</tr>
<tr>
<td>$B^+$ (5279)</td>
<td>$D^\pm$, $B^0$, $\ldots$</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$B^-$</td>
</tr>
<tr>
<td>$B^0$ (5279)</td>
<td>$D^\pm$, $B^0$, $\ldots$</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>$B^0$</td>
</tr>
<tr>
<td>$\Upsilon$ (9460)</td>
<td>Various</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Self</td>
</tr>
</tbody>
</table>
1. What is the average binding energy per nucleon for $^{13}_6C$, whose atomic mass is 13.003355 $u$? (See the page of constants for other relevant masses).
   a) 7.23 $MeV$
   b) 7.47 $MeV$
   c) 7.71 $MeV$
   d) 64.8 $MeV$
   e) 787 $MeV$

2. Which of the following statements about the strong nuclear force is false?
   a) It causes radioactivity to occur.
   b) It is much stronger than the gravitational force between two nucleons separated by about 1 $fm$.
   c) It is much stronger than the electrical force between two nucleons separated by about 1 $fm$.
   d) It is charge-independent.
   e) It is short-range.

3. What is the ratio of the nuclear volume of $^{207}_{82}Pb$ to that of $^{24}_{12}Mg$?
   a) About 6.8
   b) About 1.0
   c) About 8.6
   d) About 1.9
   e) About 2.1

4. For a certain radioactive substance, it is found that 25% of the nuclei decay in 3.0 hours. What is the half-life of the substance?
   a) About 12 hours
   b) About 7.2 hours
   c) About 0.75 hours
   d) About 1.5 hours
   e) About 6.0 hours
5. Which of the following statements is false?
   a) When a nucleus undergoes $\beta^+$ decay, the charge of the nucleus decreases.
   b) When a nucleus undergoes $\beta^-$ decay, a neutron in the nucleus turns into a proton.
   c) When a nucleus undergoes $\beta^-$ decay, the Q-value (decay energy) is negative.
   d) When a nucleus undergoes $\beta^+$ decay, the Q-value (decay energy) is positive.
   e) When a nucleus undergoes $\gamma$ decay, the charge of the nucleus remains unchanged.

6. The $^{14}$C isotope is radioactive with a decay constant $\lambda = 1.21 \times 10^{-4}$ yr$^{-1}$. All living organisms have an activity of 0.255 decays/second per gram of carbon. If a certain dead organism is found to have an activity of 0.060 decays/second per gram of carbon, how long ago did it die?
   a) Between 1000 and 10000 years ago
   b) Less than 10 years ago
   c) More than 10000 years ago
   d) Between 10 and 100 years ago
   e) Between 100 and 1000 years ago

7. Consider the nuclear reaction $^4_2He + ^{14}_7N \rightarrow ^{17}_8O + ^1_1H$. The atomic masses are $M(He) = 4.002603$ u, $M(N) = 14.003074$ u, $M(O) = 16.999133$ u, $M(H) = 1.007825$ u. What is $Q$, the net kinetic energy released, and what conclusion can be drawn from the sign of $Q$?
   a) $Q = +1.19$ MeV, so some kinetic energy was converted to mass
   b) $Q = +1.19$ MeV, so some mass was converted to kinetic energy
   c) $Q = -1.19$ MeV, so the reaction can’t occur
   d) $Q = -1.19$ MeV, so some kinetic energy was converted to mass
   e) $Q = -1.19$ MeV, so some mass was converted to kinetic energy
8. Which of the following statements are true?

- I: The sun releases energy because hydrogen nuclei are undergoing fusion.
- II: Stars whose mass is much smaller than that of our sun will eventually turn into neutron stars or black holes.
- III: When $^{235}U$ undergoes fission into $^{144}Ba$ and $^{89}Kr$, energy is released because $U$ has more binding energy per nucleon than do $Ba$ and $Kr$.

a) III is true; I and II are not  
b) I and II are true; III is not  
c) All three statements are false  
d) I and III are true; II is not  
e) I is true; II and III are not

9. Only one of the following reactions or decays CANNOT occur. Which is it? For the reactions, assume that the projectile always has enough energy for the reaction to occur, if other applicable conservation laws permit).

a) $\nu_\mu + p \rightarrow n + \mu^+$  
b) $\pi^- + p \rightarrow n + \pi^0$  
c) $\bar{p} + p \rightarrow n + \bar{\pi}$  
d) $p + p \rightarrow p + p + p + \bar{p}$  
e) $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

10. Which of the following statements is false?

a) In any reaction, the number of baryons (minus anti-baryons) is conserved.  
b) In any reaction, the number of mesons (minus anti-mesons) is conserved.  
c) In any reaction, the number of leptons (minus anti-leptons) is conserved.  
d) Anti-baryons are composed of three anti-quarks.  
e) Mesons are composed of one quark and one anti-quark.
11. An electrically neutral particle has strangeness $-1$, charm 0, and bottomness $+1$. Which of the following is a possible quark composition for this particle?

a) $s\bar{b}$

b) $b\bar{s}$

c) $us\bar{b}$

d) $\bar{u}s\bar{b}$

e) $c\bar{s}\bar{b}$

12. Consider the hypothetical strong interaction process $B^+ + \Sigma^- \rightarrow \Lambda_b^+ + D_s^- + D^0$. Which conservation laws does it satisfy, and which does it violate?

a) Conserves strangeness, but neither charm nor bottomness

b) Conserves charm and bottomness, but not strangeness

c) Conserves strangeness and bottomness, but not charm

d) Conserves strangeness and charm, but not bottomness

e) Conserves bottomness, but neither strangeness nor charm

13. A photon strikes a stationary proton, causing the following reaction to occur: $\gamma + p \rightarrow \Lambda + K^+$. What is the minimum energy $E$ that the photon must have if this reaction is to occur?

a) $E < 650\,\text{MeV}$

b) $650 \leq E < 750\,\text{MeV}$

c) $750 \leq E < 850\,\text{MeV}$

d) $850 \leq E < 950\,\text{MeV}$

e) $E \geq 950\,\text{MeV}$

14. According to the General Theory of Relativity, which of the following statements are true?

- I: The effects of acceleration and gravitation cannot be distinguished in a closed laboratory.

- II: To an external observer, a black hole contracts forever towards its Schwarzschild radius, but never quite gets there.

- III: The path of light is unaffected by gravity.

a) All three statements are true

b) I and II are true; III is false

c) I and III are true; II is false

d) I is true; II and III are false

e) III is true; I and II are false
15. The Lyman alpha line of hydrogen has a wavelength of 122 nm in the laboratory. For a certain galaxy, the same line is measured to have a wavelength of 300 nm. How far away is the galaxy?
   a) About $2.0 \times 10^9$ light years
   b) About $4.0 \times 10^9$ light years
   c) About $6.0 \times 10^9$ light years
   d) About $8.0 \times 10^9$ light years
   e) About $1.0 \times 10^{10}$ light years

16. An antiproton of kinetic energy 1200 $MeV$ moves to the right. A proton of kinetic energy 400 $MeV$ moves to the left. The two collide head-on, producing the reaction $\bar{p} + p \rightarrow \pi^0 + X$. What is the maximum mass of $X$ that can be produced in this way?
   a) About $3341 \ MeV/c^2$
   b) About $2762 \ MeV/c^2$
   c) About $3476 \ MeV/c^2$
   d) About $1819 \ MeV/c^2$
   e) About $3204 \ MeV/c^2$