Physics 390: Practice Exam

This is a final exam from a previous year. This year's final exam will have basically the same format. The first part of the exam will contain short multiple choice questions, each worth two points. You **do not** need to show your working for these questions. Just circle the correct answer. The remaining pages of the test will contain longer questions for which you do need to show working. You may use your copy of the book "Modern Physics" by Tipler & Llewellyn, your class notes, and the solutions to homeworks, either your own or those handed out in class. Electronic versions of the textbook will be allowed. You may use a calculator (or a calculator app on your phone) for doing arithmetic.

Indicate your answer to each question by circling its letter.

1. What is a typical value for the work function of a metal?

   (a) 0.4 MeV
   (b) −4 eV
   (c) 4 MeV
   (d) 4 eV

2. To two significant figures, what is the wavelength of the peak in the emission spectrum of a black body at 1000°C?

   (a) 2.3 μm
   (b) 2.9 μm
   (c) 2.3 nm
   (d) 2.9 nm

3. What is the internal energy of an ideal gas of N particles (assuming rotational and vibrational energy can be ignored)?

   (a) $\frac{1}{2}NkT$
   (b) NkT
   (c) $-\frac{3}{2}NkT$
   (d) $\frac{3}{2}NkT$

4. What is the approximate ground-state energy of a single electron in a cubic box 10^{-10} m on a side?

   (a) 1 eV
   (b) 10 eV
   (c) 100 eV
   (d) 1000 eV

5. What is the approximate range of the weak force?

   (a) 10^{-18} m
   (b) 10^{-15} m
   (c) 10^{-13} m
   (d) 10^{-11} m

6. Which of the following neutron reactions proceeds via the electromagnetic force?

   (a) $n + \pi^+ \rightarrow p + \gamma$
   (b) $n + e^+ \rightarrow p + \overline{\nu}_e$
   (c) $n + \pi^+ \rightarrow p + \pi^0$
   (d) $n \rightarrow p + e^- + \overline{\nu}_e$

7. What is the velocity of an alpha particle with kinetic energy 10 MeV?

   (a) $2.2\,\text{ms}^{-1}$
   (b) $22\,\text{ms}^{-1}$
   (c) $2.2 \times 10^3\,\text{ms}^{-1}$
   (d) $2.2 \times 10^7\,\text{ms}^{-1}$

8. Which of the following particles is *not* massless?

   (a) Neutrino
   (b) Graviton
   (c) Photon
   (d) Gluon

9. What is a typical radius for an atomic nucleus?

   (a) 4 μm
   (b) 4 nm
   (c) 4 pm
   (d) 4 fm

10. How does alpha decay change the atomic number Z and mass number A of a nucleus?

    (a) $A \rightarrow A - 2$ and $Z \rightarrow Z - 2$
    (b) A stays constant and $Z \rightarrow Z - 1$
    (c) $A \rightarrow A - 4$ and $Z \rightarrow Z - 2$
    (d) A stays constant and $Z \rightarrow Z + 1$

The rest of the test consists of longer questions. Each one is worth ten points. **For full points, show clearly how you arrive at your answers.**

1. **A two particle system:** A simple system consists of two identical noninteracting bosons with spin zero that can each be in either of two states having energies $-E$ and $+E$. The system is in thermal equilibrium at temperature T.

   (a) **[3 points]** Write down the partition function for the system.

   (b) **[3 points]** Hence or otherwise find an expression for the average energy of the whole system as a function of temperature.

   (c) **[4 points]** Thus show that the heat capacity of the system is

   $$C = \frac{8E^2}{kT^2} \frac{(2 + \cosh(2E/kT))}{(1 + 2\cosh(2E/kT))^2}.$$

   where k is Boltzmann's constant.

2. **Neutrinos:** A free neutron decays to a proton $n \to p + e^- + \overline{\nu}_e$ with a lifetime of about fifteen minutes.

   (a) **[1 point]** Which of the four fundamental forces is responsible for this decay?

   (b) **[3 points]** Calculate the combined kinetic energy that the electron and the neutrino carry off after the decay. (You can ignore the kinetic energy of the proton, which is very small.)

   (c) **[4 points]** Current estimates put the mass of the electron antineutrino at 0.2 eV. Suppose all of the kinetic energy in the decay goes into such a neutrino. Estimate the difference $c - v$ between the speed of the neutrino and the speed of light.

   (d) **[2 points]** If such a neutrino were emitted on the far side of the galaxy, 100 000 light years away, and a photon were emitted at the same time, both traveling towards Earth, the photon would arrive first followed by the neutrino. About how long would the time interval Δt be between their arrivals?

3. **Decays of subatomic particles:** For each of the following reactions, state whether the process indicated is an allowed decay (i.e., whether the process will happen spontaneously to an isolated particle if one waits long enough). If allowed, state which of the four fundamental forces is responsible for the decay. If forbidden, state which conservation law is violated. (Hint: You will probably want to make use of Tables 12-6, page 604, and 12-11, page 620.)

   (a) **[2 points]** $n \to p + e^- + \overline{\nu}_e$

   (b) **[2 points]** $\Lambda^0 \to \pi^+ + \pi^-$

   (c) **[2 points]** $\pi^- \to e^- + \gamma$

   (d) **[2 points]** $\Delta^- \to n + \pi^-$ (Δ^- is three d-quarks and has mass 1232 MeV)

   (e) **[2 points]** $\Lambda^0 \to p + K^-$

4. **Scattering of α particles:** In their experiments on scattering from atomic nuclei, Ernest Rutherford and his students used a radioactive α-particle source given them by Marie Curie. The active ingredient of the source was the isotope ^{214}Po.

   (a) **[3 points]** From the mass data given in the book, calculate the kinetic energy in MeV of the α particles emitted by this source.

   (b) **[2 points]** Derive an expression for the closest distance r an α particle with kinetic energy E can come to a nucleus with atomic number Z in the Rutherford scattering experiment.

   (c) **[1 point]** The radius of a nucleus is given, to a good approximation, by $R = R_0 A^{1/3}$, where A is the number of nucleons. What is the value of the constant R_0?

   (d) **[3 points]** Making the simple approximation that $A \simeq 2Z$, show that the highest value of Z for which an α particle with energy E penetrates the nucleus is

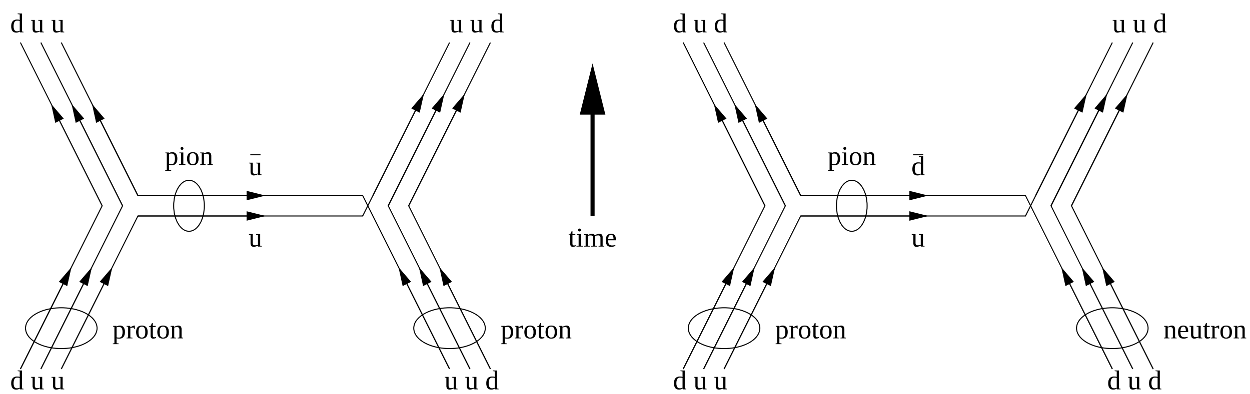
$$Z = \sqrt{\frac{R_0^3 E^3}{4k^3 e^6}},$$

   where k is the Coulomb constant.

   (e) **[1 point]** For Rutherford's α particles, which element does this correspond to?

5. **Extra credit:** An approximate theory of the force between nucleons was proposed by Yukawa in 1935. He suggested that the force was the result of the exchange of virtual pions (i.e., the particles π^+, π^-, and π^0). Pions are bosons and so they can mediate a force, just as photons do, but they are not fundamental particles, because they are made of smaller ones, quarks. Still, if we look only at phenomena that take place on length scales much larger than the size of a pion, so they can be treated as point particles to a good approximation, the theory is quite accurate.

   Here are two examples of exchanges of pions between nucleons, with the quark composition of each particle shown explicitly:



   Note that in the second case the interaction also results in the proton and the neutron swapping identities. This is because the charged pions carry flavor.

   (a) **[3 points]** Of the three pions, which can be exchanged between (i) a proton and a neutron, (ii) two protons, and (iii) two neutrons?

   (b) **[2 points]** Based on the known mass of the pions, about how long can a virtual pion last?

   (c) **[2 points]** Hence what is the maximum range of the force between nucleons? How does this compare with the observed range of the force?

   (d) **[3 points]** Consider the reaction $\Sigma^+ + n \rightarrow p + \Lambda^0$. Draw a sketch similar to the one above, showing the quark composition of the particles in this reaction and of the meson exchanged. What is the name of this meson? (Hint: There is more than one correct answer to this question. Any correct answer will get the points.)