Physics 390: Homework 10

For full credit, show all your working.

1. **Cosmic rays:** The particles with the highest known kinetic energies are not those created in particle accelerators, but the particles we call "cosmic rays," which are mostly protons, accelerated to extraordinary energies by who-knows-what mechanism somewhere in the universe.

   (a) The highest energy protons ever observed have kinetic energies on the order of 10^{20} eV. Calculate the relativistic γ-factor $\gamma = 1/\sqrt{1 - v^2/c^2}$ for such a particle and hence estimate the difference $c - v$ between the particle's velocity and the speed of light.

   (b) If a baseball weighing 150 g had the same kinetic energy, how fast would it be traveling?

   (c) If you were riding along with such a proton in its frame of reference, how long would it take (in that frame of reference) to cross our galaxy from one side to the other, allowing for relativistic Lorentz contraction? The galaxy is about 100 000 light years in diameter.

2. **Fundamental forces:** Which of the four fundamental forces is responsible for each of the following processes?

   (a) $n \to p + e^- + \overline{\nu}_e$

   (b) $\pi_0 \to \gamma + \gamma$

   (c) $\Delta^+ \to \pi^0 + p$

   (d) $\pi^+ \to \mu^+ + \nu_\mu$

3. **Conservation laws:** Which of the follow processes is allowed and which is forbidden? For the forbidden ones, state which conservation law or laws is broken in each case:

   (a) $p \to n + e^+ + \nu_e$

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

   (c) $p + \overline{p} \to \gamma + \gamma$

   (d) $n \to p + \pi^-$

   (e) $\nu_e + p \to n + e^+$

4. **Proton mass:** The masses of the up and down quarks are 2.4 MeV and 4.8 MeV.

   (a) What is the combined mass of the three quarks in a proton? How does this compare to the observed mass of the proton?

   (b) The quarks in a proton have kinetic energy on account of the uncertainty principle—we know their location very accurately, so their momentum cannot be zero. Use the uncertainty principle to make a rough estimate of the momentum of a quark trapped in a volume of radius about 1 fm (the radius of a proton). Show that the quark is traveling close to the speed of light. Taking this into account, estimate the kinetic energy of the quark.

   (c) Adding the mass energy and the kinetic energy together, how much total mass should the proton have? How does this compare with the observed mass of the proton?