Massachusetts Institute of Technology
Department of Physics

Physics 8.033 21 November 2006

Quiz 2

Name: (Last, First) ______________________________ (please print).

Recitation number (circle one): 1 2 3

- Record all answers and show all work in this exam booklet. If you need extra space, use the back of the page.
- All scratch paper must be handed in with the exam, but will not be graded.
- This exam is closed book. You may use your handwritten notes if they are clearly labeled with your name and you hand them in with your exam.
- Whenever possible, try to solve problems using general analytic expressions. Plug in numbers only as a last step.
- Please make sure to answer all sub-questions.
- Good Luck!

Problem	Max	Grade	Grader
1	25		
2	25		
3	25		
4	25		
Total	100		

Question 1: Quick answers [25 Points]

(a). **(5 pts)** Consider the following reactions:

(A) ______________ A 100 MeV photon decays into an electron-positron pair.
(B) ______________ A neutron decays into an electron-positron pair and a photon
(C) ______________ A neutron decays into a proton, an electron and a neutrino.
(D) ______________ A proton decays into a neutron, a positron and a neutrino.
(E) ______________ A neutron decays into a proton and a photon.

For each one, write **one** of the letters from the option list below.

L violates lepton number conservation
B violates baryon number conservation
P violates parity conservation
E violates energy-momentum conservation
Q violates charge conservation
N violates none of the above conservation laws

(b). **(9 pts)** Give each of the following quantities to the nearest power of 10 (don't show calculations, being off by one power of 10 is OK):

(A) ______________ Age of our universe when most He nuclei were formed
(B) ______________ Age of our universe when hydrogen atoms formed
(C) ______________ Age of our universe today
(D) ______________ Number of stars in our Galaxy
(E) ______________ Light travel time to closest star (Sun!:) in minutes
(F) ______________ Hydrogen binding energy in eV/c^2
(G) ______________ Electron mass in eV/c^2
(H) ______________ Neutron mass in eV/c^2
(I) ______________ Light travel time to 2nd closest star in years

(c). **(9 pts)** Indicate whether each of the following statements are true of false.

(A) TRUE / FALSE If our Universe is only X billion years old, then we can only see objects that are now less than X billion light years away
(B) TRUE / FALSE Space must be infinite, because it cannot end with a boundary without more space on the other side.
(C) TRUE / FALSE Leptons do not feel the strong interaction.
(D) TRUE / FALSE No experiment inside an isolated sealed lab in space can distinguish between whether it is uniformly accelerating or in a uniform gravitational field.
(E) TRUE / FALSE A clock by the ceiling runs faster than one by the floor.
(F) TRUE / FALSE Hubble's law implies that the Big Bang was an explosion localized near the comoving position of our Galaxy.
(G) TRUE / FALSE The expansion of our galaxy is governed by the Friedmann equation.
(H) TRUE / FALSE Two galaxies can recede from each other faster than the speed of light.
(I) TRUE / FALSE We know that our entire observable universe was once at infinite density

(d). **(2 pts)** A tritium (H^3) nucleus contains ______ up quarks and ______ down quarks.

Question 2: The Proton-Proton Cycle [25 Points]

In the Sun, one of the processes in the He fusion chain is $p+p+e^- \to d+\nu$, where d is a deuteron. Make the approximations that the deuteron rest mass is $2m_p$, and that $m_e \approx 0$ and $m_\nu \approx 0$, since both the electron and the neutrino have negligible rest mass compared with the proton rest mass m_p.

(a). For the arrangement shown in the figure, where (in the lab frame) the two protons have the same energy γm_p and impact angle θ, and the electron is at rest, calculate the energy E_ν of the neutrino in the rest frame of the deuteron in terms of θ, m_p and γ.

(b). For the special case where the deuteron remains at rest in the lab frame and $\theta = 30°$, solve for γ and calculate the energy of all particles (the deuteron, the neutrino, one of the protons) in terms of the proton rest mass m_p.

Question 3: Coulomb's Law generalized `[25 Points]`

In an inertial fram S, the position $\mathbf{r}_q$ of a point charge q moves according to $\mathbf{r}_q(t) = v\hat{\mathbf{z}}t$, i.e. with velocity v in the $\hat{\mathbf{z}}$-direction, passing the origin at $t = 0$. In the moving frame S' where the charge is at rest at the origin, Coulomb's law states that the electric field is

$$E' = A\frac{\mathbf{r'}}{r'^3},$$

where $A = q/4\pi\varepsilon_0$. Show that in the frame S, the electric field at $t = 0$ is s

$$\mathbf{E} = A\frac{(1-\beta^2)}{(1-\beta^2\sin^2\theta)^{3/2}}\frac{\mathbf{r}}{r^3},$$

where θ is the usual polar angle ($z = r\cos\theta$, $x^2 + y^2 = r^2\sin^2\theta$).

Question 4: Cosmology [25 Points]

(a). **(10 pts)** Consider a particle coasting in the r-direction (i.e., with constant θ and ϕ) in a flat FRW metric, with no non-gravitational forces acting on it. Use variational calculus to prove that $p \propto 1/a$ (here $p = m_0\gamma u$ is its momentum and $u \equiv a\dot{\mathbf{r}}$ is its velocity relative to nearby comoving observers).

(b). **(2 pts)** Given a), the value of u in the limit $a \to 0$ is __________.

(c). **(2 pts)** Given a), the value of u in the limit $a \to \infty$ is __________.

(d). **(2 pts)** Thus relative to comoving observers, your results show that an object without external forces in an expanding universe
(circle one) REMAINS IN UNIFORM MOTION / SLOWS DOWN / ACCELERATES.

(e). **(3 pts)** Starting with the answer from a), derive how the wavelength λ of a photon depends on a. Your answer should be of the form $\lambda \propto$(function of a).

(f). **(6 pts)** Solve the Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

to obtain a solution of the form $a(t) \propto$ (function of t) for the case where space is flat and the density is dominated by photons, and compute the age of the universe at the time when $H^{-1} = 30$ seconds.