Physics 715 **Final exam** **May 2, 2005**

1. Some magnets have tendencies to both ferromagnetism characterized by the appearance of the order parameter M, and antiferromagnetism characterized by the appearance of the order parameter A. The Gibbs free energy G for one such system has the form

$$G = \frac{1}{2} r_F (T - T_F) M^2 + u M^4 + \frac{1}{2} r_A (T - T_A) A^2 + u A^4.$$

r_F, r_A, u, T_M, and T_A and v are positive constants that are independent of temperature. They satisfy $T_F = T_A/2$ and $r_F = 5 r_A$. T is the temperature.

(a) Find the phase transition(s) in this system as a function of T. Indicate which are first order transition(s) and which are second-order transition(s).

(b) For the first-order transition(s), calculate the latent heat of the transition(s); for the second-order transition(s), calculate the discontinuity in the specific heat.

2. In the early universe at times $t < 10\ ms$, all the constituents of the universe listed below were present in great profusion. They were in thermal equilibrium with each other at a single temperature T.

(a) Which of these particle species have survived to the present day?

(b) For those which haven't, approximately when did they disappear? Give your answer in both time and temperature units, and explain how you came to your conclusion.

(c) Some of the particle species went out of equilibrium with the others. Which ones?

(d) At what time and temperature did this happen for each? Why? What has happened to these particles since then?

symbol	*particle*	$mc^2\ (MeV)$	$mc^2/k_B\ (10^{10}\ K)$
e^-, e^+	*electron, positron*	0.51	0.592
$p, \bar{p}$	*proton, antiproton*	938.3	1088
$n, \bar{n}$	*neutron, antineutron*	939.6	1090
$\nu_e, \bar{\nu}_e$	*electron(anti)neutrino*	$< 1.8 \times 10^{-5}$	$< 2 \times 10^{-5}$
$\nu_\mu, \bar{\nu}_\mu$	*muon(anti)neutrino*	< 0.25	< 0.29
$\nu_\tau, \bar{\nu}_\tau$	*tau (anti)neutrino*	< 35	< 40.6
μ^-, μ^+	*muon, antimuon*	105.6	122.5
τ^-, τ^+	*tau, antitau*	1784	2069
γ	*photon*	0	0