229B HW # 1 (due Sep 17, 12:30)

1. The neutrino cross section is approximately given by $\sigma_\nu \sim G_F^2 s/\pi$, where $s = (p + P)^2$ is the squared center-of-momentum energy of the neutrino (four-momentum p^μ) and the target (four-momentum P^μ).

(1) What is the possible final state from $\nu_e n$ scattering and $\bar{\nu}_\mu p$ scattering? Draw Feynman diagrams for the two processes.

(2) Estimate the cross sections in cm^2 for νe scattering and νn scattering when e, n are at rest and $E_\nu = 10$ MeV.

(3) Estimate the mean free path of 10 MeV neutrino through lead.

2. On February 23, 1987, a supernova (named SN1987A) exploded in Large Magellanic Cloud, which is about 50 kpc away from the Earth. Kamiokande Collaboration and IMB Collaboration detected a burst of neutrinos and reported them in K. Hirata *et al.*, *Phys. Rev. Lett.* **58**, 1490 (1987), `http://prola.aps.org/abstract/PRL/v58/p1490_1`; R.M. Bionta *et al*, *Phys. Rev. Lett.* **58**, 1494 (1987), `http://prola.aps.org/abstract/PRL/v58/i14/p1494_1`. Answer the following questions.

(1) Calculate the energies of neutrinos using the table of events in Hirata paper, from the observed electron (actually believed to be positron) energies and the angles from the SN1987A direction for each of them. Assume that all events are caused by the reaction $\bar{\nu}_e p \to e^+ n$, and neglect the error bars.

(2) Obtain an upper bound on the neutrino mass. Since the energy of neutrinos varied from one event to another, a massive neutrino would have different velocities and hence different arrival times. The observed spread in the arrival times is consistent with the expected duration of the neutrino burst of a few seconds. Therefore there is no significant broadening in the arrival time beyond the level of a few seconds. From this consideration, one can place an upper bound on the neutrino mass. (The last three events arrived more than 9 seconds later from the first event, and there is a dispute if they came from SN1987A. Discard them and use only the first 9 events.)