1) <u>Conservation laws.</u> For each of the following reactions, (a) establish whether it is allowed or not; (b) if it is not, give the reasons (there may be more than one); (c) establish the interaction that allows it.

$p+\overline{p} \;\rightarrow\; \Lambda^\circ + \Lambda^\circ$

$p \;\rightarrow\; n+e^+$

$\mu^+ \;\rightarrow\; \nu_m + e^+$

$e^+ + e^- \;\rightarrow\; \nu_\mu + \overline{\nu}_\mu$

$p+p \;\rightarrow\; \Sigma^+ + \pi^+$

$\Sigma^0 \;\rightarrow\; \Lambda^0 + \gamma$

$D^- \;\rightarrow\; K^+ + \pi^- + \pi^-$

$\Lambda^0 + p \;\rightarrow\; K^- + p + p$

2) <u>Upper bound on neutrino mass</u> from supernova explosion SN1987A. On 23.2.1987 a supernova explosion was observed in the Great Magellan Cloud that is 1.54 x 10^{18} km = 1.63 x 10^5 light years away. So the event happened 1.63 x 10^5 years ago. Two neutrino detectors independently observed a short burst of neutrinos with energies between 35 and 13 MeV within a 10 second time interval. Assume the neutrinos all started out at the same moment. Show that for two neutrinos with energies E_1 and E_2 the difference in arrival times is

$$\Delta t = t_2 - t_1 \approx \frac{Lm^2}{2c}\left(\frac{1}{E_2^2} - \frac{1}{E_1^2}\right)$$

Use this expression and the data to derive an upper bound for the neutrino mass. L = 1.5 x 10^{18} km.

3) <u>Neutron-Antineutron oscillation</u>. If the baryon number is conserved, the transition $n \leftrightarrow \overline{n}$, known as "neutron oscillation" is forbidden. The experimental limit on the time scale of such oscillations in free space is $\tau_{n\leftrightarrow\overline{n}} \;\geq\; 3 \;x\; 10^6 s$. Let H_o be the Hamiltonion in the absence of any interaction which mixes n and $\overline{n}$. Then:

$$H_o|n\rangle = m_n c^2|n\rangle \quad , \quad H_o|\overline{n}\rangle = m_n c^2|\overline{n}\rangle$$

for states at rest. Let H' be the interaction which turns n into $\overline{n}$ and vice versa:

$$H'|n\rangle = \varepsilon|\overline{n}\rangle \quad , \quad H'|\overline{n}\rangle = \varepsilon|n\rangle$$

where ε is real and H' does not flip the spin.

Start with a neutron at t = o and calculate the probability that it will be observed to be an antineutron at time t. When the probability is first equal to 50%, call the time $\tau_{n\leftrightarrow\overline{n}}$. In this way convert the experimental lower limit on $\tau_{n\leftrightarrow\overline{n}}$ into an upper limit on ε.