International Neutrino Summer School 2009 Tutorial Questions

1) ICE Cube reconstructs one event that looks like a 200 TeV double bang event. Come up with a strategy for proving to yourself and the community that it is a real tau neutrino charged current interaction.

2) Imagine that KATRIN finds a neutrino mass of 336 meV. Assume that the lepton number violating process in double-beta decay is from light Majorana neutrino exchange. Assuming that the cost for neutrino-less double beta decay experiments scales as mass, define and defend an experimental strategy for one or a series of double beta decay experiments. Possible complications to consider: what if these experiments had backgrounds? What if there were other LNV processes contributing to double beta decay? What are the implications of constraints related to observational cosmology?

3) If the weak interaction conserved parity, what would be the consequences for the relative rates of two-neutrino and neutrinoless double beta decay for a given set of neutrino masses?

4) Assuming that neutrinos are Majorana particles and that the lepton number violating process is a light Majorana neutrino exchange. What does one conclude if neutrinoless double beta decay experiments do not observe any decays?

5) A terrorist organization is developing nuclear weapons in secret. Assuming the location of their lab is known, work out parameters for a neutrino monitor of your design that would be able to pick up nuclear tests or production of fuel at a nuclear reactor.

6) A reactor experiment measures $\sin^2 2\theta_{13} = 0.10\pm0.01$. How would you optimize the combination of neutrinos and antineutrinos for NOvA to run at to determine the mass hierarchy? (To simplify this question, assume that θ_{23} is exactly 45 degrees, but that δ is unknown)

   What if the reactor experiment measures $\sin^2 2\theta_{13} = 0.01\pm0.003$? Now how would you optimize NOvA to determine the mass hierarchy under the same assumptions about θ_{23} and δ?

7) Use GLOBES to design an experiment to measure the density of the core of the earth with neutrinos.

8) Imagine you had control over the arrangement of cores and operations of a 10 GWatt (thermal) nuclear reactor complex. Design a reactor experiment to measure the mixing angle θ_{13} as precisely as possible.

9) Focusing on the detector issues, design an experiment to determine what quadrant θ_{23} is in.

10) For a low energy neutrino factory experiment doing muon sign appearance, design the best large area magnetized detector. (Use detector simulations and some estimate of the costs of magnetizing a big area).

11) Calculate the number of nubar_e + p → e^+ + n events in the Kamiokande-II detector expected from SN 1987A. Make reasonable assumptions until your result mostly agrees with the actual measurement. Assume a perfect detector efficiency.

    Using the number of events detected in the Kamiokande-II detector from SN 1987A, consider strategies to detect neutrinos from other supernovae. Supernovae in individual galaxies are rare. If you consider more than one galaxy, the total supernova rate is larger, but the yield per supernova is lower. Thinking about detection outcomes, how do galaxies at different distances compare?

12) Assuming that the ^{7}Be solar neutrinos radiatively decay in flight with a lifetime τ via the reaction $\nu_2 \rightarrow \nu_1 + \gamma$, with $m_1 \sim 0$, calculate the flux of decay photons as a function of the assumed τ /m for ν_2. What can you estimate about the spectrum of these photons? Make an estimate of the τ /m limit by bounding the rate of photon appearance.

13) Standard leptogenesis requires that the light neutrinos are Majorana particles, and prefers that their masses are lighter than 0.1-0.2 eV. Suggest ways in which future experiments can weaken the case for leptogenesis, or even falsify it.

14) Consider the neutrino mixing matrix

    $$U_{BM}=1/2\{\{\sqrt{2},-\sqrt{2},0\},\{1,1,-\sqrt{2}\},\{1,1,\sqrt{2}\}\}.$$

    Write down the most general neutrino mass matrix that corresponds to this mixing matrix in the basis where charged leptons are diagonal.

15) At present discrete groups are considered as possible flavor groups. The group S3 is the group of permutations of 3 objects. It has 6 group elements. Prove that they can be written as products of 2 operators S and T with S^2=T^3=(ST)^2=1. This group has 3 irreducible representations 2, 1, 1' of dimension 2, 1 and 1 respectively. Write down the explicit forms of S and T for these representations in a basis for the 2 where T is diagonal. Write the multiplication table for the irreducible representations and try to derive the Clebsh Gordan coefficients.

16) In a SU(5)xU(1) model the U(1) charges of Ti=10, Fi=5bar, Ni=1 (i=1,2,3 is a generation index) are Ti=(4,2,0), Fi=(2,0,0), Ni = (1, -1,0) [(4,2,0) means 4 for generation 1, 2 for generation 2 and 0 for generation 3]. The Higgs fields carry no U(1) charges). Two SU(5) singlet flavon fields Y, Y' with charges -1 and 1 resp. take VEV's and break U(1). Write the mass matrices of up and down quarks, of charged leptons, and the Dirac and Majorana masses for neutrinos. Discuss, as far as you can, the mass ratios that emerge and the mixing angles.

17) Since we know that neutrinos are massive, the heavier ones can decay radiatively to the lighter ones via a loop diagram. First estimate the lifetime of the neutrinos. (Don't actually do the loop calculation, but estimate it from a textbook calculation of b to s gamma which involves the same sort of loop diagram.) Next, analyze whether the radiation from neutrino decay could be used to detect cosmic neutrinos. This requires some consideration of the background radiation from other astrophysical and cosmological sources, which can be found in the book by Kolb and Turner

18) The KATRIN neutrino mass experiment and follow-ups measure null results while results from Planck and other observations yield a positive measurement in the mass range supposedly ruled out by the direct measurements. How would you explain this discrepancy? What alterations in cosmology are implied by the discrepancy? Don’t be afraid to discard any standard assumptions about cosmology, neutrino properties, reliability of experimental methods, etc., as long as you are not violating observable results known today.

19) Design one or several near detectors for a long baseline wide band neutrino oscillation experiment looking for θ_{13}. Assume a neutrino flux similar to either the T2KK or LBNE (Fermilab to DUSEL) proposals: that is, on axis broad band neutrino flux. What are the strengths and weaknesses of your near detector proposal?

20) Design a detector (or detectors) to provide an in situ flux measurement that would operate at a conventional (pion-based) neutrino beam long baseline experiment. What sort of near detector (or detectors) would you choose to measure flux for a beta beam experiment or a long baseline neutrino factory experiment? (No near detector at all might be a reasonable choice, but you would have to explain why that’s a good idea.)

21) Assume there are only three neutrino mass eigenstates. Suppose that the ν_μ and ν_τ fractions of the isolated mass eigenstate in the spectrum, ν_3, are both exactly 0.49. Suppose further that the ν_μ and ν_τ fractions of the mass eigenstate ν_2 are both exactly 0.33. (These numbers are similar to what is seen experimentally, although the assumption that they are exactly

known is unrealistic). Assuming the given flavor fractions, show that the CP-violating difference, $P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e)$, is necessarily non-zero at some L/E.

Questions 22 through 24 will make use of code make use of code that Mark Messier has set up at the following web site: http:enrico1.physics.indiana.edu/messier/nss09

22) Compute the event length for muon neutrino charged-current events and neutrino neutral-current events assuming a water detector. Fill two 1D histograms with event length in cm on the x-axis and counts on the y-axis for the Charged Current and Neutral Current events. Plot the two histograms overlaid.

Do the same as above, but now make the x-axis on the histograms in units of the interaction length of the detector. Are the event lengths of the Neutral Current events over or under estimated? Can you think of a better representation of the Neutral Current event lengths?

Still working with the event lengths, plot in 2D the event length in cm vs. neutrino energy for muon neutrino Charged Current events and Neutral Current events. Make a plot with the 2D histograms side-by-side. Also plot the two distributions as profile histograms one overlaid on the other. Repeat all these steps for an iron detector. Compare to the water case.

23) Plot the fraction of neutral-current events which have at least one π^0 in the final state as a function of neutrino energy for energies between 0 and 10 GeV in bins of 1 GeV. Assuming a Super-Kamiokande-like detector plot the fraction of neutral-current events which have at least one pi0 in the final state as a function of visible energy, for energies between 0 and 10 GeV in bins of 2 GeV. Define the visible energy in the following way:

- electrons : total energy
- other charged particles: (K.E.) - (K.E. at threshold)
- Photons : total energy
- π^0 : total energy
- All others : 0

Assume the index of refraction for water is n=1.33 For Neutral Current interactions, select events with at least one π^0. Compute random conversion points in the detector for the two photons assuming a NOvA-style detector (scintillator with density 0.86 g/cm^3). Plot the fraction of events which have:

- distance to first conversion point is less than 36 cm (6 NOvA planes)and
-distance between conversion points is less than 48 cm (8 NOvA planes)

Make the plot as a function of visible energy between 0 and 10 GeV in bins of 2 GeV. The visible energy is computed as it is in the Super-Kamiokande case, but without the Cherenkov threshold.

24) For a MINOS-style detector, compute the significance of the charge sign determination (k/sigma_k) as a function of neutrino energy between 0 and 30 GeV.

Fill a 2D histogram with energy on the x-axis and significance on the y-axis. Plot the average significance using the "ProjectX" option.

Some useful parameters:
MINOS is 2.54 cm thick iron planes
1.00 cm thick solid scintillator plane
1.00 cm air gap
Transverse segmentation: 4.1 cm
B field 1.4 T

Repeat the above exercise for a magnetized version of the NOvA detector. Some useful parameters:

NOvA is 6 cm planes of liquid scintillator
Transverse segmentation: 4 cm
B field 0.5 T

Group	Choice of Questions	Group	Choice of Questions
A	1,9,17	L	4,12,20
B	2,10,18	M	5,13,21
C	3,11,19	N	6,14,22
D	4,12,20	O	7,15,23
E	5,13,21	P	8,16,24
F	6,14,22	Q	1,9,17
G	7,15,23	R	2,10,18
H	8,16,24	S	3,11,19
I	1,9,17	T	4,12,20
J	2,10,18	U	5,13,21
K	3,11,19	V	6,14,22

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