Andre de Gouvea – Lecture 1 Questions

Questions marked in green were answered during the Q&A session. I haven't tried to correct grammer/spelling. Where a slide number was given it is shown.

Q1 (slide 1/2): Is there any theoretical motivation for why lepton number should be conserved? Some hidden symmetry?

A1: In the Standard Model of particle physics, lepton number is exactly conserved and the conservation is, not surprisingly, associated to an accidental global U(1) symmetry of the Lagrangian. Accidental means it is a symmetry we did not ask for but arises as a "side effect" of the particle content of the model and the gauge symmetries. I will talk more about this in Lecture 2.

Q2 (slide 3): Does neutrino oscillations break generation lepton number? As we are converting electron nu to some other flavour

A2: (also answered live). Yes, neutrino oscillations explicitly break lepton-flavor number (electron number, muon number, tau number). The source of the lepton-flavor violation is the leptonic mixing matrix. If the matrix were trivial (proportional to the identity or some permutation of the identity) lepton-flavor numbers would be conserved and neutrino oscillation would be impossible.

Q3 (slide 2): The way we identify neutrino flavour is by seeing what charged lepton it is coming with. That means we assume that charged leptons flavour and mass basis is same for experiments right? What if that basis is different, then if we obeserve electron which say is in mass basis, then can we make some statements about the neutrino obeserved?

A3: We can choose, without loss of generality, the mass basis and the charged-current interaction basis to be the same for either the charged-leptons or the neutrinos, but not both. The Physics does not depend on what choice we make but, as usual, some choices are more convenient than others and it is easiest to describe the phenomena of interest in the basis we normally pick for neutrino oscillations.

Q4: We usually do neutrino physics in quantum mechanics. Since they are relativistic particles, why are we not using quantum field theory as it describes relativistic particles consistently

A4: We can use QFT for describing neutrino oscillations, but there is nothing wrong with using QM. The key point is that, when computing the amplitudes associated to the experiments of interest, the overwhelming contribution comes from the one-particle neutrino and charged-lepton states; their propagation is governed by the Schrodinger equation. (In QFT, the oscillations are part of the neutrino propagator (see diagram in my slide on page 4). At the end of the day, the answer we get is the same.

Q5 (intro): what does coherence really mean?

A5: In this context, it means that, for example, when we say that pion decays into a muon and a neutrino, the neutrino is described as a quantum linear superposition of mass eigentstates. As a pure state - this is where the coherence comes in - interference happens: this is the where we get the oscillations. If the neutrinos were not produced coherently, the situation would be different. In the case of pion decay, we would say the neutrino is either a nu_1 or a nu_2 or a nu_3, and that these “come out” with certain probabilities. In this case, there woud be flavor change since a nu_1, when it interacts, it can produce either electron, muons, or taus, but there would be no oscillation; i.e., the flavor change would not depend on time. In the case of quarks, we normally view weak decays as producing incoherent mixtures of different quarks. For example, the D+ meson can decay into pi^+ K0 or pi^+ pi^0, with different probabilities. We never get a linear superposition of K0 and pi^0. The reason for this is that neutrino masses are tiny.

Q6: Throughout the lecture   What is baseline?

A6: The baseline is the distance between the neutrino source and the neutrino detector. It is usually referred to as L.

Q7: Could you please elaborate on the statement "neutrino production and detection must be COHERENT"? what exactly coherence means here?

A7: see A5 above. The idea is that the object produced and detected is a quantum linear superposition of mass eigenstates and NOT a statistical mixture of mass eigenstates.

Q8: In the "matter effects" slide: why the evolution is given by non-relativistic hamiltonian, while we neutrinos are relativistic? I'm assuming that is why we can use L and t interchangeably.

A8: The idea is that the equation that governs the distance-evolution of the neutrino flavor in the ultra-relativistic approximation looks like the Schrodinger equation for a non-relativistc, discrete QM system. The reason we use t and L interchangeably is that the neutrinos are ultrarelativistic. A neutrino, after some time t, travels a distance L = ct. This turns out to be an excellent approximation.

Q9: Is it possible to explain neutrino oscillation only by matter effects (with zero neetrino mass) using a well-suited neutrino non standard interaction (or neutrino-dark matter interaction)?

A9: (also answered live) Wolfenstein, in his seminal paper on matter effects, was looking for a mechanism that accomplished exactly that. If there are more interactions than the standar model ones, and if the new interactions violate lepton-flavor, it is possible to have matter effects induce flavor change. This is not a solution to all neutrino oscillation data. However, we still look for the effects of non-standard neutrino interactions in oscillation experiments. They could impact things, at a subleading level.

Q10: If muon neutrinos were propagating through a background of muons would they also pick up a matter potential term?

A10: Yes. And if the neutrinos were propagating through a background of positrons the sign of the potential would be flipped.

Q11: If you do the 2 flavor approximation (i.e oscillation probability from electron to muon neutrino), which is the theta considering the 3 theta parameter of PMNS matrix?

A11: I am sorry I did not get to explain this. It depends on the experiment. For solar neutrinos, theta is, to a great approximation, theta_12. For the disappearance of atmospheric muon neutrinos, theta is theta_23. For short-baseline reactor neutrinos (L about 1km, like Daya Bay and RENO), theta is theta_13. There are two reasons the two-flavor approximation holds. 1- theta_13 turns out to be small so long-baseline experiments involving electron neutrinos tend to see the Delta m^2_12 and theta_12 effect more prominently (this happens for KamLAND and solar neutrinos). 2- Delta m^2_13 is much larger than Delta m^2_12 soo if you do an experiment with a baseline that is not too long, you don't see Delta m^2_{12} effects (this happens for atmospheric neutrinos and almost all accelerator experiments like NOvA, T2K, etc; it also happens for Daya Bay, Double-Chooz and RENO).

Q12: At higher order (including loop diagrams) I could imagine the neutrinos also interacting with the photon fields of the nuclei in the earth. How will such effects impact the neutrino oscillations? At what energies might they play a role?

A12: These effects are very, very tiny and many of them are flavor-indifferent (they treat all flavors the same and hence do not impact oscillations). They would matter only if they could overshadow the "regular" matter effects and not for any specific neutrino energy.

Q13: Currently your approach to attack neutrino oscillations is quantum mechanics. Is there any consistent and complete QFT description for it? Any references? Thanks!

A13: see the answer to A4. There is a more-or-less recent discussion here: https://arxiv.org/pdf/1001.4815.pdf It also includes other references.

Q14: How do we know neutrinos leave the sun in the heavier eigenstate instead of the lighter eigenstate? I lost my connection for a bit so maybe I just missed it.

A14: (answered live) The fact that the solar neutrinos leave the Sun as the heavy mass-eigenstate (in the two-flavor approximation) is because the sign of the matter potential is positive for neutrinos. The situation is the opposite for electron antineutrinos. if they were produced in the Sun like the electron neutrinos - they are not! - they would exit the Sun as the lightest mass eigentstate.

Q15: Isn't there a slight tension between solar and reactor data?

A15: There is a slight tension between solar data and data from KamLAND (reactor experiment). This tension was reduced - it is still there, but weaker, a little less than 2 sigma - with new data from Super-Kamiokande, presented in the Neutrino 2020 conference.

Q16: How do we know the neutrino propagation in the sun is adiabatic?

A16: This is determined by comparing Delta m^2/E with the rate of change of the electron number density inside the Sun (from the center to the surface). The answer turns out to be - keep in mind we know the density of electrons in the Sun very well, along with the neutrino energies - adiabatic, but it did not need to be this way. A long time ago, the data were also consistent with other values of Delta m^2, some of which led to a less adiabatic scenario.

Q17: Unlike the quark sector we do not talk about charged leptons mixing, though just from the Lagrangian PMNS matrix seems to be able to do all CKM matrix can. How do we get to this conclusion, theoretically and experimentally?

A17: see answer to A3. We could choose to talk about charged-lepton mixing, the physics does not depend on how we choose to describe the weak-interaction vertices. This choice however, would not be the smartest choice.

Q18: How do the matter effects differ for electron-neutrinos and electron-antineutrinos?

A18: The matter potential is positive for electron neutrinos and negative for electron antineutrinos. One way to understand this is that the W-boson is a spin one particle (like the photon) so it couples with one charge with matter and the opposite charge to antimatter (like the photons do).

Q19: Do neutrinos released from Z boson decay oscillate?

A19: (answered live) The answer depends on what the question is, exactly. If we could measure the flavor of the neutrinos (or antineutrinos) produced in Z decay, we would ⅓ nu_e, ⅓ nu_mu and ⅓ nu_tau. These fractions would not change as a function of the baseline. What makes neutrinos from Z decay interesting is that flavor of the neutrino and the antineutrino are correlate, like an EPR pair. If we measure the neutrino side and it behaves like a muon neutrino, the antineutrino will behave like a muon antineutrino with 100% probability if you measure it immediately after the measurement is performed in the neutrino side. More generally, you can flavor-tag the neutrino (or the antineutrino) at any point in time by measuring the flavor of the sister antineutrino (or neutrino). The flavor-tagged species would even oscillate after that.

Q20: When we talk about neutrino oscillations, do ever take into account neutrino to antineutrino oscillations?

A20: Historically, oscillations were first considered in the context of neutrinos oscillating to antineutrinos (this was inspired, indirectly, on K - Kbar oscillations); this was a long time ago and does not make sense today. On the other hand, if neutrinos are Majorana fermions, there should be phenomena that look like neutrino to antineutrino oscillations. They require lepton number to be violated - I will mention this in lecture 2 - and the effects, compared with the standard neutrino to neutrino oscillations, are absurdly small. I have a (in my opinion) nice paper that talks about this: https://arxiv.org/pdf/hep-ph/0211394.pdf

Q21: (not familiar with neutrino physics theory much)What is the motivation for defining the neutrino masses in the way they are defined? Does it come from the PMNS matrix constraints?

A21: This is historical but has a practical reason. If we defined the neutrino masses in a different way - the most obvious one would be m_1 < m_2 < m_3 - the ambiguity related to the mass ordering would not go away, of course. Instead, for the different mass-orderings, the form of the mixing matrix would be different (something like U_e1 would be replaced with U_e3, etc). This would be very cumbersome.

There is another definition that people like to use: nu_1 has the most “electron” in it, nu_2 the second most and nu_3 the least (|U_e1|^2 > |U_e2|^2 > |U_e3|^2). The reason I prefer not to use it is that it makes use of an external object - the mixing matrix - to definite the mass eigenvalues, which is not necessary.

Q22: Is there any fundamental reason for why the 3 mass eigenstate seem to have the same amount of muon and tau neutrino ?

A22: (answered live) We don’t know. It is a curious fact and something that is addressed by research in lepton flavor models.

Q23: What if neutrinos are Majorana type, what consequences are relevant from this scenario?

A23: because neutrino masses are tiny, as far as oscillations are concerned, Dirac and Majorana neutrinos are the same, for all practical purposes. If they were different, we might be able to tell them apart! I will talk more about the nature of the neutrino in the second lecture.

Q24: How does we account for the sterile neutrino in the mass oscilation matrix?

A24: (answered live) The easiest way to think about new neutrino states is to add more mass-eigenstates (i.e. nu_4, nu_5, nu_6, etc). These, in general, can have a nonzero probability of being measured as e, mu, or tau flavors (i.e., U_e4, U_mu4, U_tau4, etc don’t need to be zero). It is still the case that |U_e1|^2 + |U_e2|^2+|U_e3|^2 + |U_e4|^2+... = 1, which means there are more flavors than e, mu, tau. We usually assume they are sterile - this means they don’t couple to the W or Z - because a different assumption is ruled out experimentally. The total number of flavor states (including the sterile ones) is the same as the total number of mass states. So, if there are five mass eigenstates, there are three active flavors: e, mu, tau, and two “sterile” flavors (e.g. s_1, s_2).

Q25: What do you mean by "test the formalism" on your final slide?

A25: I will talk more about this in the second lecture.

Q26: how does hierachy changes with a sterile neutrino? Now we can have all sort of possibilities of putting m4 in the picture?

A26: Yes, absolutely. The two hierarchies we talk about in the case of three neutrinos are all possible hierarchies. With 4 neutrinos, there are many more. They fall into 2 “classes,” referred to as 2+2 and 3+1. To visualize the 2+2 case, add a nearby mass to the solitary state in one of the three-flavor hierarchies in slide 32. To visualize the 3+1 case, add a fourth state “far away” from the three known states. In the context of the short-baseline anomalies - the strongest motivation for sterile neutrinos -

there are no viable 2+2 solutions and we usually talk about the 3+1 case. We also concentrate on the hypothesis that the 4th state, which is mostly sterile, is much heavier than the other three. This is required by the KATRIN bound and the bound on neutrino masses from cosmology.